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Thermodynamic performance analyses and optimization of subcritical and transcritical organic Rankine cycles using R1234ze(E) for 100–200 °C heat sources

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ABSTRACT

The working fluid has a crucial effect on the thermodynamic performance of the organic Rankine cycle (ORC) system. Trans-1,3,3,3-tetrafluoropropene, R1234ze(E), is a new-typed environmental friendly and safe organic fluid that presents a great potential to be used in ORC systems. This study focuses on subcritical and transcritical ORCs using R1234ze(E) driven by the 100–200 °C hot water without the outlet temperature limit. For various heat source temperatures, the optimal cycle type (subcritical or transcritical), optimized cycle parameters (turbine inlet temperature and turbine inlet pressure), and system performance were studied in the view of the maximum system net power output for the per mass flow rate heat source fluid. Results show that the transcritical ORC has a higher system efficiency, whereas its system heat absorption capacity is lower than that of the subcritical ORC for R1234ze(E). The subcritical ORC is more suitable for heat source temperatures below 160 °C with the transcritical ORC for higher temperatures. For subcritical and transcritical ORCs using R1234ze(E), the optimized turbine inlet temperature and turbine inlet pressure for various heat source temperatures among 100–200 °C were also provided. Compared to R245fa and R600a, the maximized system net power output of R1234ze(E) is the largest for the approximately 100–167 °C heat sources without the outlet temperature limit, and it is 31.4% larger than that of R245fa at most and 25.8% larger than that of R600a at most.

1. Introduction

Renewable energy utilization and waste heat recovery are important approaches to solve the global energy shortage and environmental pollution. Exploring the suitable development technology for various energy sources has attracted the attention all over the world. Organic Rankine cycle (ORC) is a heat-power conversion technology which is based on the principle of the Rankine cycle and uses low boiling point organic fluids as working fluids [1]. It has advantages of wide applicable heat source temperature range, high efficiency, simplicity, stability, flexibility, safety and wide installed capacity range [1–3]. ORC presents a great potential to utilize the medium to low temperature heat sources (<350 °C), and many scholars have been attempting to use the ORC system to utilize the biomass energy, geothermal energy, solar energy and various waste heat sources [1–16]. The application of ORC systems is continuously expanding.

In an ORC system, the working fluid is an important carrier for achieving the power generation from heat sources, and it crucially affects the system performance [3–8]. Common working fluids for ORC systems include the hydrochloroflurocarbons (HCFCs), hydroflurocarbons (HFCs), hydrocarbons (HCs) and siloxanes at present [1,7]. HCFCs, HFCs and light HCs are usually used for heat sources below 200 °C, such as geothermal energy, solar energy with simple collectors and several waste heat sources [1,3,5–10]. While, the heavy HCs and siloxanes are usually used for heat sources of approximately 200–350 °C, such as biomass energy, solar energy with concentrated solar collectors, waste heat from engine exhaust and industrial flue gas [7–11]. Several scholars have focused on the analyses of the ORC thermodynamic performance and optimization of cycle parameters for specific organic fluids. These scholars have made significant contributions to the practical application of organic fluids in ORC systems [9,12–18]. However, the environmental performance requirements of organic

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Nomenclature

g	gravitational acceleration (9.8 m s^{-2})	cool	cooling water
H	pressure head (m)	cond	condenser or condensation
h	specific enthalpy (kJ kg^{-1})	e	evaporator or evaporation
m	mass flow rate (kg s^{-1})	in	inlet
p	pressure (MPa)	ip	inflection point
Q	heat flow rate (kW)	max	maximum
s	specific entropy (J kg^{-1} K^{-1})	min	minimum
T	temperature (°C)	net	net power
W	power (kW)	O	organic working fluid
ΔT	temperature difference (°C)	out	outlet
		P	feed pump
Greek symbols		pp	pinch point
η	efficiency	sat	saturation condition
		sys	system
Subscripts		T	turbine
1–7	state points shown in Fig. 2	vap	vapor generator
c	critical state	w	hot water

fluids have been restricted by the international community through the enforcement of several international environmental protection agreements, such as Montreal Protocol (1989) and its subsequent amendments, Kyoto Protocol (2005) and Paris Agreement (2016). HCFCs are being phased out because their ozone depletion potential (ODP) generally exceed 0 which indicates their ability to destroy the ozone layer. HFCs are being phased out because of their large (generally several thousand) global warming potential (GWP) that promotes the greenhouse effect. Furthermore, the application of HCs in ORC systems remains restricted by the inflammability and explosion risks. Exploring the new-type environmental friendly and safe working fluids for ORC systems is extremely urgent.

Trans-1,3,3,3-tetrafluoropropene, R1234ze(E), is a new-type low-GWP organic fluid that belongs to hydrofluoroolefins (HFOs). It contains a carbon-carbon double bond and is easily decomposed in the air. The GWP_{100} of R1234ze(E) is 6 and its ODP is 0. R1234ze (E) is nontoxic and its safety classification is A2L which is permissible for commercial applications [19]. Therefore, R1234ze(E) is a promising organic fluid with broad applications. Many scholars have measured the thermophysical properties of R1234ze(E) that contributes to its further thermodynamic performance analysis and practical application [20–24].

Attempts to use R1234ze(E) have been made in the refrigerating and heat pump systems by certain scholars [23,25–27]. For instance, Fukuda et al. [25] utilized thermodynamic, numerical and experimental methods to assess the performance of R1234ze (E) in a high temperature heat pump system. Their results showed that the system COP of R1234ze(E) was larger than those of R410A and R134a, and R1234ze(E) has potential applications in high temperature heat pump systems. Molés et al. [26] evaluated the theoretical energy performance of R1234ze(E) in the various single stage vapor compression refrigeration configurations. Their results showed that the system COP of R1234ze(E) increased by 11–20% compared to that of the basic cycle using R134a when an expander or an ejector was adopted as an expansion device. Jankovic' et al. [27] compared the performance of R1234ze(E) and R134a in a small power refrigeration system. Their results showed that R1234ze(E) performed better than R134a when an overridden compressor was adopted. Few scholars also attempted to use R1234ze(E) in ORC systems [28–30]. For instance, Le et al. [28] analyzed the thermodynamic performance of a transcritical ORC using R1234ze(E) driven by 150 °C hot water. Their results showed that R1234ze(E) had the maximum electric power among eight working fluids. Yang and Yeh [29] and Yang et al. [30] focused on the working fluid selection of the subcritical ORC for the exhaust waste heat recovery of diesel engines. Their heat source temperatures are 180 °C [29] and approximately 200–370 °C [30], respectively. R1234ze(E) was both selected as an alternative in their studies, and results showed that R1234ze(E) presented the remarkable thermodynamic performance in the ORC system.

Although R1234ze(E) has the potential for broad and practical application in ORC systems, studies on ORC systems using R1234ze(E) remain insufficient and many problems still require investigation. Firstly, the 100–200 °C heat sources are common and abundant in the renewable energy (e.g., geothermal energy and solar energy with flat plate collectors) and waste heat sources (e.g., thermal oil and cooling liquid in chemical processes) [3,5,7,10]. Given its relatively low critical temperature (109.37 °C), the alternative cycle type of R1234ze(E) increases (subcritical or transcritical) for heat source temperatures of 100–200 °C; because the transcritical ORC using R1234ze(E) can be attained for the heat source temperature above 109.37 °C, theoretically. While, the optimal cycle type and optimized cycle parameters (turbine inlet temperature and turbine inlet pressure) of R1234ze(E) remain indeterminate for various heat source temperatures among 100–200 °C. Secondly, although few scholars have studied the thermodynamic performance of ORC systems using R1234ze(E) and even compared their performance with others organic fluids, all of these studies were based on the specific heat source temperature and specific cycle type. Furthermore, the heat source temperature range investigated in the present studies has not covered and is considerably lower than the temperature range of 100–200 °C. Therefore, the thermodynamic performance of ORC systems using R1234ze(E) and their advantages compared to others organic fluids still need to be studied for various heat source temperatures among 100–200 °C and various cycle types.

This paper focuses on subcritical and transcritical ORCs using R1234ze(E) driven by the 100–200 °C hot water without the outlet temperature limit. The optimal cycle type (subcritical or transcritical), optimized cycle parameters (turbine inlet temperature and turbine inlet pressure) and ORC system performance were studied for various heat source temperatures in the view of the maximum system net power output for the per mass flow rate (kg s^{-1}) heat