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Research Paper

Experimental analysis and comparison between CO_2 transcritical power cycles and R245fa organic Rankine cycles for low-grade heat power generations

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HIGHLIGHTS

- Two test rigs with CO_2 and R245fa power cycles were developed and measured.
- The effects of operational parameters on the system performance were analyzed.
- Heat transfer analyses of CO_2 gas generator and R245fa evaporator were conducted.
- The test results and analyses are essential to enhance both systems' operations.

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ABSTRACT

In this study, experimental investigations were conducted on two different test rigs to investigate and compare the performances of CO_2 transcritical power cycles (T-CO_2) and R245fa organic Rankine cycles (ORC) for low-grade heat power generations. Each test rig consisted of a number of essential components including a turboexpander with a high speed generator, finned-tube air cooled condenser, liquid pump and plate-type gas generator/evaporator. The exhaust flue gases from an 80 kWe micro-turbine CHP unit were utilised as heat sources for both T-CO_2 and R245fa ORC power generation systems and hot thermal oil flow was applied commonly as a heat transfer medium. Both test rigs were fully commissioned and instrumented from which comprehensive experimental investigations were carried out to examine the effects of various important operational parameters on system performance. These include working fluid mass flow rate and heat source input etc. at constant heat sink (ambient) parameters. Results showed that with a fixed heat source input, the turbine power generation and overall efficiency of the R245fa ORC or T-CO_2 system could be improved significantly at higher working fluid mass flow rates. Quantitatively, when the CO_2 and R245fa mass flow rates increased respectively from 0.2 kg/s to 0.26 kg/s and from 0.23 kg/s to 0.27 kg/s, the corresponding turbine power generation increased by 88.2% and 27.3% while the respective turbine overall efficiency enhanced by 35.4% and 7.5%. On the other hand, the turbine power generation and overall efficiency of the R245fa ORC or T-CO_2 system increased variably with higher heat source input when the working fluid mass flow rate is fixed. In percentage, when the heat source inputs of the T-CO_2 and R245fa ORC systems increased respectively from 52 kW to 60 kW and 61 kW to 68 kW, the corresponding turbine power generation increased 47.7% and 63% while the respective turbine overall efficiency enhanced 8.65% and 1.08%. In addition, the cycle point temperatures and pressures of both systems revealed similar increments at higher working fluid mass flow rates or at higher heat source inputs. Furthermore, heat transfer analyses of both CO_2 gas generator and R245fa evaporator can be used to set up efficient controls of working fluid superheating at the heat exchanger outlet. The test results and analyses are essential in evaluating and comparing both systems' operations at different operating conditions, design structures and components, and can significantly contribute towards optimal component selections and system performance controls.

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Nomenclature

h	enthalpy (J/kg)
I	exergy destruction (W)
$\dot{m}$	mass flow rate (kg/s)
s	entropy (J/kg K)
T	temperature (K)
W	power generation (W)

Greek symbols

η	efficiency

Subscripts

all	overall
c	calculated
e	electrical
ex	exergy
f	working fluid
is	isentropic
m	mechanical
t	turbine
0	dead state
1	turbine inlet
2	turbine outlet

1. Introduction

Over the last few decades, there has been extensive waste thermal energy discharged into the atmosphere in various forms of industrial waste or exhaust flue gases from engines and turbines. This is accumulating in serious risks of global warming, environmental pollution and fossil fuel crises. On the other hand, inexhaustible renewable energy such as solar, geothermal, biomass energies can be utilized around the world. Notably, these waste heat and renewable sources are categorized mostly into low grade thermal energy [1]. Therefore, there is an urgent obligation to generate power using low-grade thermal energy and applicable thermodynamic power cycles such as the organic Rankine cycle (ORC) [2], transcritical power cycle (TPC) [3], Brayton cycle [4] and trilateral flash cycle [5]. Even so, for heat resources such as industrial waste heat and renewable energy with low temperatures ranging from 100 °C to 350 °C, the ORC and TPC systems prove to be promising thermodynamic processes for converting low-grade heat to electricity.

The ORC functions similarly to a century-old steam Rankine power plant, but instead uses an organic working fluid such as R245fa. When applied to a low-grade heat source, the system with ORC is expected to generate power at a higher efficiency and greater cost-effectiveness than that of steam Rankine cycle [6]. Nevertheless, the constant temperature evaporating behaviour of a pure fluid in a conventional ORC results in a pinch point and a mismatch between the temperature profiles of the working fluid and a sensible heat source fluid, which can introduce significant irreversibilities [7,8]. On the other hand, in a TPC, a working fluid with relatively low critical temperature and pressure can be compressed directly to its supercritical pressure and heated to its supercritical state before expansion. Therefore, the heating process of a TPC does not pass through a distinct two-phase region like a conventional organic Rankine cycle, resulting in a better thermal match in the heat exchanger with less irreversibility [9]. Even so, challenges for the ORC and TPC systems include the choice of the appropriate working fluids with high efficiency operation, low cost, safety and less environmental impact etc. [10–12] and the particular design of the cycles. As it is difficult to find the working fluids of ORC and TPC systems that can meet all of the above criteria, four working fluids Benzene, Toluene, p-Xylene, R123 and R113 were investigated in an ORC system for their thermal efficiency and irreversibility. The results of this research showed that the ORC with p-Xylene had the highest thermal efficiency while the ORCs with R123 and R113 had the least irreversibility in recovering a low temperature thermal energy [13]. Although R1234yf and R1233ze are recently under consideration as working fluids with lower level of GWP to replace R245fa, these refrigerants are still fairly new and most of the ORC expansion machines still use R245fa as the working fluid in the current market [14]. In the meantime, mixture working fluids have been examined in attempt to improve ORC system performance and reversibility for low grade thermal energy conversions [15]. The study indicated that the use of suitable zeotropic mixtures as working fluids for the ORC system may lead to improved system performance and reversibility. In terms of system components, the expander is the main component for an ORC system, as it can determine the system's final power generation, efficiency and cost effectiveness. Thus, various experimental investigations have been carried out to evaluate and compare system performance when different expanders were used. Compared with the screw [16] and scroll [17] expanders, the turbine expander offered more advantages in terms of smaller size, lower cost, compact structure and higher efficiency [18,19]. A small scale R245fa ORC test rig with a radial-type turbine and a number of supersonic nozzles was developed to regulate the mass flow rate at dynamic thermal energy supplies [20]. As such, the ORC system can operate at optimal operating conditions by adjusting the total inlet temperature, mass flowrate, and rotational speed of the turbine. In addition, it is understood that the rotational speed, expansion ratio, mass flow rate and turbine size have significant effect on turbine performance. Accordingly, mean-line design and three-dimensional computational fluid dynamics analysis were integrated for both micro axial and radial-inflow turbines with five organic fluids and at low-temperature heat sources in ORC cycles [21]. The results showed that n-pentane had the highest performance at all design conditions in terms of maximum total-to-total efficiency and power output. Furthermore, a single stage axial turbine expander coupled with a permanent magnet synchronous generator was tested on a small-scale ORC system with working fluids of R245fa and HFE7100 [18]. It was found that the system evaporating pressure, pressure drop across the turbine and system mass flow rate had significant effect on the turbine and system performance. However, for the ORC system, the turbine expander inlet superheat temperature needs to be precisely controlled to ensure the expander's dry operation as it will affect the system power generation.

It is worth noting that the working fluids used in ORC system such as R245fa are mostly HFCs, which have relatively high Global Warming

Table 1
The properties for R245fa and CO_2 (R744).

Substance	Thermophysical data				Environmental data		
	Molecular mass	T_b (°C)	T_c (°C)	P_c (Mpa)	Atmospheric (yr)	ODP	GWP
R245fa	134.05	15.1	154	3.65	7.6	0	1030
CO_2 (R744)	44.01	−78.4	31.1	7.38	> 50	0	1