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Experimental investigation of an organic Rankine cycle with multiple expanders used in parallel

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HIGHLIGHTS

- A novel ORC with multi expanders in parallel (PE-ORC) was proposed for varied heat.
- The proposed PE-ORC were experimentally evaluated with two parallel expanders.
- Higher performances was achieved in PE-ORC than in a BORC when heat input was low.
- Dynamic test led to several control techniques for performance improvement.
- The PE-ORC could be one of the competitive design options for large heat variation.

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ABSTRACT

A novel organic Rankine cycle (ORC) with multiple expanders used in parallel (PE-ORC) is proposed for the efficient recovery of waste heat in applications in which there are typically large variations in the amount of heat produced, such as in heavy vehicles and in distributed energy systems with multiple internal combustion engines. The feasibility and the fundamental characteristics of the proposed PE-ORC were experimentally evaluated by establishing an ORC loop with two parallel expanders and testing the performance of the system in different operating modes and in dynamic tests. The PE-ORC was found to be capable of achieving a higher efficiency and a higher total power output than was achieved using a basic ORC configuration when conditions changed from those for which the basic ORC was designed, but the PE-ORC operating mode was changed to suit the new conditions. The proposed PE-ORC could therefore be a better design than is currently available for ORCs that are subject to large variations in the amounts of waste heat produced.

1. Introduction

Environmental issues and the impacts of rising energy costs have driven an increasing interest in low-grade heat recovery. The organic Rankine cycle (ORC) is considered to be a suitable basis for producing useful power from low-grade heat sources, such as solar thermal [1,2] and geothermal sources [3,4], and industrial waste heat [5]. ORCs are currently being used in a number of field applications [6–8]. A range of studies aimed at bringing ORC technology to a mature state have focused on improving performance by modifying ORC system configurations [9], developing expansion machines [10–12], selecting the most effective working fluids [13,14], and/or using mixtures of working fluids [15]. In terms of configuration, the ORC loops proposed in previous studies can be broadly categorized into basic ORCs (BORCs), regenerative ORCs [16,17], ORCs with dual expanders used in series [18–20], transcritical ORCs [10,21], two-stage ORCs [22], and ejector ORCs [23]. However, further research is required to improve the efficiency of the heat recovery, targeted at specific applications.

The Internal Combustion Engine (ICE) has been widely used to generate power and for transportation because of its high efficiency, reliability, and the variety of different fuels that can be used. ICEs are generally used in distributed energy systems in which efficient waste heat recovery is possible and where grid capacity can be used efficiently. Large amounts of energy are, however, still released to the environment from ICEs as heat in the exhaust gases and the jacket coolants, even though advanced technologies have been used to decrease these losses. It has recently been estimated that around 60% of fuel energy could still be being lost from ICEs as

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Nomenclature

$\dot{E}$	exergy (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
N	rotational speed (rpm)
P	pressure (bar)
$\dot{Q}$	heat power (kW)
T	temperature (°C)
V	swept volume/rev (m^3)
$\dot{W}_{sh}$	shaft power (kW)
η	efficiency (%)
τ	torque (N m)
ϕ	filling factor
ω	angular speed of expander (rad/s)

Subscripts

c	cycle
C	cooling water
cd	condenser
ev	evaporator
$ex1$	Expander 1
$ex2$	Expander 2
H	heat source
i	isentropic
in	inlet
out	outlet
pp	pump
r	working fluid
tot	total

waste heat [24]. Therefore, the recovery of waste heat from ICEs has become an important issue; better performance in this area would decrease fuel consumption rates and reduce the emission of waste products. The use of ORCs as reliable techniques for recovering waste heat from ICEs has been the main focus of research in this area [9,24,25].

Vaja and Gambarotta [25] determined the power that could be recovered from the exhaust gas of a 3 MW ICE using three different ORC configurations. They used a BORC preheated with the engine cooling water and a regenerative ORC. Peris et al. [9] determined the waste heat that could be recovered in simulations using six ORC configurations, namely a BORC, a regenerative ORC, a double regenerative ORC, a reheat-regenerative ORC, an ejector ORC, and a transcritical regenerative ORC. Choi et al. [26] suggested that a dual loop system could be used to recover waste heat and generate power from the exhaust gases from the main engine of a container ship. The proposed dual loop consisted of a trilateral cycle and a preheated ORC using water and R1234yf as the respective working fluids. He et al. [27] proposed a combined thermodynamic cycle consisting of an ORC and a Kalina cycle that could be used to recover waste heat from an ICE. The ORC would be used to recover the waste heat in the lubricant and exhaust gas, and the Kalina cycle would be used to recover the waste heat in the low-temperature cooling water. However, while the foregoing studies focused on constant waste-heat production by ICEs, the recovery of variable amounts of waste heat produced by an ICE has not yet been considered.

Power plants that use ICEs are usually designed to allow multiple engine configurations to be used so that the amount of power generated can be controlled. The flexible operation of a power plant to meet fluctuations in the demand for electricity could lead to variability in the total amount of waste heat in the exhaust gas and jacket cooling water. Even the waste heat produced by a vehicle with a single engine can vary considerably during a typical journey. Choi et al. [26] determined the exhaust gas temperature and fuel consumption probability distributions from real engine operation data for a container ship during a single one-way journey of about two weeks. The distributions showed that the waste heat produced by an ICE in a heavy vehicle varies appreciably but that the exhaust gas temperature does not. In these typical applications, a general ORC system designed for a single set of conditions, usually for the average amount of waste heat that the ICE produces, could frequently operate under conditions outside those for which it is designed.

In this paper, we propose a novel ORC configuration with multiple parallel expanders for the efficient recovery of waste heat from ORC applications with large variations in the amount of heat produced. To the best knowledge of authors, there is no report on an ORC with multiple expanders in parallel. The size of the proposed parallel-expanders ORC (PE-ORC) should be variable because each expander can be switched on and off. The feasibility of the proposed ORC and its fundamental characteristics were evaluated by creating and testing a simple PE-ORC system with two expanders.

2. The parallel-expanders organic Rankine cycle system

The PE-ORC proposed here is an ORC system with multiple expanders fitted in parallel (an ORC will generally have a single expander). A simple PE-ORC system with two identical expanders is shown schematically in Fig. 1. When a large amount of waste heat is produced, the PE-ORC is operated in the dual mode, with both expanders being brought into use by opening the control valves that feed the working fluid into the expanders.

The mass flow rate of working fluid is expressed as:

$$\dot{m}_r = (V_{ex}N_{ex})\rho_{ex,in} \quad (1)$$

where V_{ex} is the expander swept volume per revolution, and N_{ex} is the rotational speed of expander. The density at expander inlet is proportional to the mass flow rate when V_{ex} and N_{ex} are fixed. Hence, the expander inlet pressure is directly affected by the mass flow rate of the working fluid since the inlet pressure is an increasing function of density. When less waste heat is produced and the PE-ORC is in the dual operating mode, the mass flow rate of the working fluid decreases to maintain the vapor quality at the entrance of the expander, so the expander inlet pressure decreases. However, using the single operating mode (achieved by closing the valve at the entrance to Expander 2) allows the pressure ratio to be increased because the swept volume will be halved.

Conceptually simulated thermodynamic cycles on a T–s diagram for the R245fa working fluid used in a PE-ORC and a BORC are shown in Fig. 2. These cycles were for a source of heat at an almost constant temperature, such as the exhaust gas from an ICE; this is one of the main target applications for the PE-ORC. The cycles clearly show that the pressure ratio in the dual operating mode dropped significantly under low heat conditions (i.e., outside the conditions for which the BORC was designed), and this was caused by a decrease in the mass flow rate of the working fluid. The low pressure ratio could cause the efficiency and the power output of each ORC to decrease. The figure also shows that a higher pressure ratio was achieved in the PE-ORC, improving its performance, by switching from the dual to the single operating mode. Assuming that the characteristics of the PE-ORC operated in dual