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Performance characteristics of a 200-kW organic Rankine cycle system in a steel processing plant

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HIGHLIGHTS

- A 200-kW ORC system was designed and manufactured to generate electricity.
- The thermodynamic performance was analyzed with an electric heat source.
- Waste heat of a steel processing plant was analyzed and prepared for heat source.
- The ORC system was installed in the plant and a site test was conducted.
- The partial-load performance of the system was analyzed.

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ABSTRACT

The main objective of this research is to design and build a 200-kW ORC system with reduced size that could be installed in a steel processing plant where space is limited. The real-time operating characteristics of the ORC system are demonstrated with actual flue gases. First, an ORC system with R245fa refrigerant was developed for a heat source temperature of 140 °C. The evaporation and condensation pressures were 2,090 kPa and 220 kPa, respectively. The net power output was 235.7 kW with a thermal efficiency of 12.9%. Using an electric heat source, the design point performance of the system is experimentally demonstrated and shows a net power output of 177.4 kW with thermal efficiency of 9.6%. The turbine isentropic efficiency and generator efficiency were 68.1% and 98.5% at a rotational speed of 14,000 rpm. Next, the ORC system was implemented by designing a dedicated heat transfer loop for a steel processing plant using data measured from a chimney. The experimental net power output is 105.8 kW with a thermal efficiency of 8.6% when the plant is operated at the highest work load. The fluctuation of the flue gas temperature is successfully suppressed with a thermal storage tank installed in the heat transfer loop. A partial-load analysis was conducted and showed that the system has the highest performance with more than 165 kW of net power output. Economic analysis of such system showed that the right sized ORC system with always working parent plant had good economics with a payback period of 9 years.

1. Introduction

In energy intensive industries, surplus heat is generated because it is not used entirely on-site [1]. Generally, high-grade heat can be recovered by application of conventional steam power plant but low-grade heat with temperature of less than 370 °C has uneconomic thermal efficiency for same steam Rankine cycle [2]. Therefore, instead of using it for heat-to-power conversion, low-grade heat is used for direct heat utilization such as office heating if necessary or it is discarded to environment [1]. However, recent advances in organic Rankine cycle (ORC) technology, unstable fuel price and an interest in protection of the environment and higher thermal efficiency attracted attention to recovery of low-grade waste heat in industry [3]. Statistical investigation also indicates that low-grade heat accounts for more than 50% of total heat

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Nomenclature

$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
N	rotational speed (rpm)
P	pressure (kPa)
$\dot{Q}$	heat rate (kW)
$\dot{W}$	power (kW)
η	efficiency
υ	specific volume (m^3/kg)
ω	angular speed of turbine (rad/s)
τ	torque (N m)

Subscripts

c	cycle
cd	condenser
cw	cold water
eV	evaporator
fg	flue gas
gen	generator
hw	hot water
i	isentropic
II	2nd law
in	inlet
meas	measured
out	outlet
pp	pump
rel	release
RTO	regenerative thermal oxidizer
s	isentropic
sh	shaft
t	total
tb	turbine
wf	working fluid

generated in industry [2]. Campana et al. [3] analyzed the heat recovery potential of energy intensive industries in 27 European countries, and they found about 20,000 GW h of thermal energy every year can be recovered using ORC.

Steel industry has the second largest heat recovery potential followed by oil&gas industry [3]. In steel industry, large amount of excess heat is generated since its production process is often conducted at high-temperature [4]. The type and temperature of waste heat is different according to processes and techniques in semi-finished casting production [3]. In the work of Campana et al. [3], a heat recovery potential in steel industry was revealed in the exhaust gas from electric arc furnace (EAF) and from rolling mills. The averaged potential power for EAF was 27.8 kW per ton processed from three audits, and that for rolling mills was 6.87 kW per ton produced every hour from six audits. Kaska [1] analyzed a different type of waste heat; the pressurized hot water produced during cooling of walking beams. Ozdil [5] also analyzed a potential in the similar hot water but in saturated state. In addition, several commercial ORC units for EAF was delivered by Turboden; a 700 kW unit for NatSteel in Singapore; a 2.7 MW unit for Elbe Stahlwerke Feralpi in Germany; a 2.2 MW unit for ORI Martin in Italy; and a 10 MW unit for Arvedi steel plant in Italy.

Mentioned above ORC is one of the promising technologies for waste heat recovery of low-to-medium temperature heat [6]. Compared to competing technologies including Sterling engines, thermoelectric systems, micro Rankine cycles and inverted Brayton cycles, ORC can provide a power output of more than 100 kW with best thermodynamic performances [7]. Compared to Kalina cycles, ORC provides similar or less net electric power for the same heat source but ORC is better because the system is simple and it does not require a high pressure technology [8]. Main feature of ORC is as follows; Conceptually, ORC has same working principle as steam Rankine cycle except for the organic working fluid with low critical temperature. This makes ORC can use mature technology of conventional steam Rankine cycle. In reality, the components are much simple because it can select dry working fluids and the complex HRSG (heat recovery steam generator) is not required. Required technology level for components such as bearing, sealing, piping and others is moderate due to the low operating temperature and pressure. Also, higher density of organic working fluids and small volumetric expansion ratio enable turbine design easier. In addition, ORC has simple system control and adjustable system size. These provide ORC both economics and robustness.

Generally, the working fluid selection and optimization of the boiler saturation temperature for some thermodynamic quantities, like cycle efficiency and heat source recovery factor are main problems for designing ORC [9]. This is because those selections can lead to opposite design choices in the achievement of maximum power output [10]. For instance, Liu et al. [11] depicted a contrary trend in thermal efficiency and heat recovery effectiveness for a given heat source condition, thus considering a single index was regarded as inappropriate. Those selections are also highly dependent on given heat source and heat sink conditions of each application [12,13]. For example, Soffiato et al. [14] designed and optimized an ORC system for LNG carrier where multiple heat sources, like the jacket water, lubrication oil and charge air cooling of the engines are present, thus various cycle configurations including simple, regenerative and two-stage, subcritical and supercritical ORCs were considered. In addition, the fluid critical temperature is related to cycle performances [11]. Vivian et al. [10] proposed general guidelines to select ORC working fluid and cycle layout, and they found the distance between inlet temperature of the heat source and fluid critical temperature plays a key role in predicting the optimum performance of all system configurations. Working fluid mixture is another method to achieve more-efficient and power-dense cycles due to non-isothermal phase at constant pressure, which reduced minimal temperature differences and decreased exergy losses [15]. Chys et al. [15] showed that ORC with suitable binary mixture working fluid produces 20% more power output and increases thermal efficiency by 15% over ORC with pure working fluids. Oyewunmi et al. [16] extended the range of mixture working fluids based on SAFT-VR Mie equation of state, which enables to predict mixture properties where experimental data are not available. In addition, economics of system can lead to different conclusions in fluid selection. For instance, Quoilin et al. [17] proposed a sizing model of the ORC and found that optimal operating conditions for a maximum power doesn't matched with that of the minimum specific investment cost. Imran et al. [18] performed thermo-economic optimization for regenerative ORC using genetic algorithm and they found that R245fa is optimum fluid for basic ORC due to its low specific investment cost and thermal efficiency. Hajabdollahi et al. [19]