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Performance analysis of a novel power/refrigerating combined-system driven by the low-grade waste heat using different refrigerants

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ABSTRACT

In this paper, a novel power/refrigerating combined-system driven by the low-grade waste heat of the flue gas was introduced. It coupled a transcritical organic Rankine cycle with a vapor compression refrigeration cycle. In order to understand basic characteristics of this novel combined-system, a detailed performance analysis was performed. Results show that the turbine inlet pressure, flue gas inlet temperature and condensation temperature are three important parameters influencing system performance. During the increase of the turbine inlet pressure, the refrigeration capacity and the exergy efficiency exhibit the maximum values. However, with the increase of the flue gas inlet temperature and the decrease of the condensation temperature, both the refrigeration capacity and the exergy efficiency corresponding to the optimal turbine inlet pressure increase. The use of regenerator can improve the system performance and reduce the optimal turbine inlet pressure. Under partial refrigeration load, there is a linear relationship between the electricity output and the refrigeration capacity at a fixed work output from the turbine. The total irreversible loss decreases and the exergy efficiency increases with the decrease of the power ratio. Finally, after screening and comparing various potential working fluids, R134a is recommended as the working fluid of this novel combined-system.

1. Introduction

With the rapid development of economy in recent years, the problems of energy shortage and environmental pollution attract the world's attention. The utilization of renewable energy and the recovery of industrial waste heat have become the effective methods to reduce fossil fuel consumption and abate the environmental problem [1–4]. Converting low-grade waste heat of the flue gas into electricity by the ORC (organic Rankine cycle) is a potential way to recover waste heat during the industrial production, and becomes a research focus of many researchers. The ORC as the basic waste heat recovery system has many advantages, such as simple construction, great flexibility, high safety, low operation cost and high waste heat recovery efficiency and so on [5,6]. Many efforts have been made to improve the system performance, including organic working fluids selection, performance analysis, parameter optimization and evaluation etc. [7–13].

During the performance improvement of the ORC, some new systems of combining the organic Rankine cycle with the refrigeration cycle have been proposed. Compared with the simple ORC system, the combined-system can provide the output of both electricity and refrigeration capacity, and shows a high thermodynamic efficiency. Because the energy consumption of the refrigeration and air conditioning equipments has become one of the largest industrial energy consumption, many researchers start to study this combined-system in the past few decades. The combined-systems are generally classified into three categories according to different refrigeration cycle [14–17]. One was proposed by Goswami [18], which combined the Rankine cycle with the absorption refrigeration cycle, and ammonia–water was used as the working fluid [19–22]. In this cycle, the conventional condensation process was replaced by an absorption condensation process. Liu et al. [23] presented the other novel advanced configuration of the combined cycle. Compared with the Goswami cycle [18], this novel cycle could obtain a good temperature match between the heat source and the working fluid, and a low turbine back pressure. Recently, Ayou et al. [24] conducted an overview of the combined power and absorption cooling cycles in existence, those cycles were divided into two types according to the utilization of sensible heat and latent heat. In conclusion, this kind of cycle can provide the output of both electricity and refrigeration

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Nomenclature

c_p	specific heat capacity, kJ/(kg K)
E	exergy, kW
h	specific enthalpy, kJ/kg
I	irreversible loss, kW
m	mass flow rate, kg/s
P	pressure, Pa
Q	heat transfer rate, kW
s	specific entropy, kJ/(kg K)
T	temperature, °C
W	work output, kW

Greek symbols

α	power ratio
ε	effectiveness
η	efficiency

Subscripts

a	air
c	condenser
comp	compressor
e	evaporator
ex	exergy
elect	electricity
g	flue gas
max	maximum
min	minimum
opt	optimal
p	pump
reg	regenerator
t	total
tur	turbine
v	expansion valve
vg	vapor generator
w	water
wf	working fluid

Abbreviations

COP	coefficient of performance
ORC	organic Rankine cycle
PRCS	power/refrigerating combined-system
TORC	transcritical organic Rankine cycle
VCRC	vapor compression refrigeration cycle

capacity. However, it has not yet been widely recognized because of some additional risks, such as the corrosion and the toxicity of ammonia.

Based on the thermodynamic analysis on the ejector refrigeration cycle, discussions about combined power and ejector refrigeration cycle were also reported. Dai et al. [25,26] performed exergy analysis of the typical combined power and ejector refrigeration cycle. The results showed that the biggest exergy loss due to the irreversibility occurred in heat addition processes, and the ejector caused the next largest exergy loss. Habibzadeh et al. [27] carried out thermodynamic analysis of an innovative combined cycle, the performance comparison of three working fluids were conducted based on classical thermodynamics. Khaliq et al. [28] presented a novel combined power and ejector-absorption refrigeration cycle, which had better thermal and exergy efficiencies than the typical combined power with the ejector refrigeration cycle. In this kind of the combined-system, the heat source in the steam ejector refrigeration cycle was extracted from the turbine. Therefore, the exergy efficiency was limited by turbine inlet pressure and turbine back pressure.

Owing to the simple configuration and high thermal efficiency, the combined power with compression refrigeration cycle was presented and studied. Jeong and Kang [29] developed a combined subcritical organic Rankine cycle and vapor compression refrigeration system. Wang et al. [30,31] analyzed the performance of this combined cycle for heat activated cooling, and compared the cycle with other thermally activated cooling technologies. Either potentially higher COP (coefficient of performance) or practical advantages could be obtained by adding a secondary heat recuperator and using different working fluids. Li et al. [32] conducted the performance evaluation of the combined cycle using different hydrocarbon working fluids. Results indicated that butane was the best working fluid for the combined cycle. Aphornratana and Sriveerakul [33] proposed a novel combined Rankine-vapor-compression refrigeration cycle, which connects the expander and the compressor together by a simple turbine-compressor unit. In this kind of cycle, the waste heat can be converted into refrigerating output effectively with less energy lose. However, at a given heat source condition, those systems can only provide a certain amount of refrigeration capacity without electricity output, and not adjust the output of refrigeration capacity by demand.

In order to provide adjustable output of both electricity and refrigeration capacity simultaneously and improve the system performance, an alternative PRCS (power/refrigerating combined-system) is proposed in this work. The novel combined-system is driven by the low-grade waste heat of the flue gas. It couples the TORC (transcritical organic Rankine cycle) with the VCRC (vapor compression refrigeration cycle). As we know, the similar combined-system has been proposed and studied extensively by many previous researches, such as Prigmore and Barber [34], Kaushik et al. [35], Jeong and Kang [29], Wang et al. [30,31] and Li et al. [32]. However, their attentions focused only on the output of refrigeration capacity. In this work, a generator-turbine-compressor unit is applied to achieve the output of both electricity and refrigeration capacity. What is more, the PRCS can provide the different proportion of electricity and refrigeration capacity. The generator-turbine-compressor unit and a shared air-condenser connect the TORC with the VCRC, and two flow regulators are used to adjust the output of electricity and refrigeration capacity. The TORC is applied to reduce the irreversible loss for the good temperature match between the heat source and the working fluid. R22, R134a and R290 are respectively chosen as the working fluid and the thermodynamic analysis of the system is performed by Engineering Equation Solver (EES) [36]. The performance comparison between basic and regenerative PRCS is also carried out.

2. System configuration descriptions

The novel power/refrigeration combined-system mainly consists of a vapor generator, a generator-turbine-compressor unit, a shared air-condenser, an evaporator, a pump, an expansion valve and two flow regulators. The schematic diagram of this system is shown in Fig. 1. Compared with the basic PRCS, a regenerator is added in the regenerative PRCS. As pointed out by Mago et al. [37], the regenerator can improve both the first and second law efficiencies.

In the PRCS, two thermodynamic cycles are the transcritical organic Rankine cycle and the vapor compression refrigeration