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Configurations selection maps of CO_2-based transcritical Rankine cycle (CTRC) for thermal energy management of engine waste heat

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HIGHLIGHTS

- A selection map of CTRC toward thermal energy management of engine.
- A rapid and effective decision-supporting tool for a general CTRC design.
- Comprehensive system performances are considered from three aspects.
- The method can be expanded to other recovery system selection.

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ABSTRACT

CO_2-based transcritical Rankine cycle (CTRC) can be used for the waste heat recovery due to its safety and environment-friendly characteristics, and also fits for the high temperature of exhaust gas and satisfy the miniaturization demand of recovery systems. It can provide a reasonable pathway toward thermal energy management of engine. This work proposes novel configurations selection maps of four CTRC configurations for waste heat recovery of engines. Except for considering a regenerator added to traditional CTRC (basic CTRC) recovering exhaust waste heat, a preheater driven by engine coolant will be also taken into account in this paper. Thus, the four configurations include the basic CTRC (B-CTRC), the CTRC with a preheater (P-CTRC), the CTRC with a regenerator (R-CTRC) and the CTRC with both of the preheater and the regenerator (PR-CTRC). As different CTRC configurations have advantage of performance indicators under different conditions, and the focused indicators may also be various with applications, this paper focuses on proposing a kind of selection maps, which is used for the selection of the four CTRC configurations in the field of engine waste heat recovery. Comprehensive performance comparison are researched in this paper from three aspects, net power output based on the first law of thermodynamics, exergy efficiency based on the second law of thermodynamics and electricity production cost (*EPC*) as an indicator of the economic performance. After the comparative analysis, three selection maps separately based on the three performance indicators are proposed to give the selection reference of the CTRC configurations under different design conditions, which refer to turbine inlet pressure and temperature in this paper. It is meaningful for the design and operating of the CTRC configuration used for waste heat recovery of engines. Besides, it can also be a new method that can be expanded to other recovery system selection (e.g. ORCs) in engine field or other fields (e.g. solar, geothermal).

1. Introduction

Over 50% of the total fuel combustion energy in an engine is wasted by the exhaust gas and the engine coolant under most design conditions, resulting in energy waste and emission problems [1,2]. Waste heat recovery and thermal energy management of engine are significant and necessary. Among the recovery technologies, organic Rankine cycle (ORC) is an efficient method. Exhaust gas waste heat is suitable to recover first due to its high temperature and large amount of heat, but it is difficult to select a suitable traditional ORC to match its extremely high temperature, which can reach about 800 °C for a gasoline engine. The most common organic fluids have relatively low thermal decomposition temperature, direct heat transfer between the fluids and the exhaust gas is infeasible. Hence, a few researches pay attention to modify the traditional ORCs, such as exploring novel fluids which has high decomposition temperature [3,4], adding an oil

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Nomenclature

Δt	mean logarithmic temperature difference (K)
A	heat transfer area (m^2)
C	cost ($)
Cp	specific heat capacity (kJ/(kg K))
d_i	inner diameter of tube (m)
d_o	external diameter of tube (m)
D_{eq}	equivalent diameter (m)
E	exergy (kW)
EPC	electricity production cost ($/kW h)
f	friction factor
G	mass flux of the working fluid (kg/m^2 s)
h	specific enthalpy (kJ/kg)
I	irreversibility (kW)
K	total heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
m	mass flow rate (kg/s)
Nu	Nusselt number
Pr	Prandtl number
Q	heat flow rate (kW)
Re	Reynolds number
s	specific entropy (kJ/(kg K))
t	temperature (K)
v	velocity (m/s)
W	work (kW)
x	vapor quality

Greek letters

α	convective heat-transfer coefficient (W/m^2 K)
δ	thickness (m)
ρ	density (kg/m^3)
η	efficiency
λ	thermal conductivity (W/m K)
μ	viscosity (Pa s)

Subscripts

bm	bare module
cond	condenser
c	engine coolant
ex	exergy
f	working fluid
g	exhaust gas
gen	generator
gh	gas heater
i	each component
in	inlet
l	liquid
max	maximum
out	outlet
preh	preheater
reg	regenerator
turb	turbine
v	vapor
1–7	state point
0	environmental state
1s, 4s	state points for the ideal case

Abbreviations

B-CTRC	basic CO_2-based transcritical Rankine cycle
CTRC	CO_2-based transcritical Rankine cycle
ORC	organic Rankine cycle
P-CTRC	CO_2-based transcritical Rankine cycle with a preheater
PR-CTRC	CO_2-based transcritical Rankine cycle with a preheater and a regenerator
PPTD	Pinch Point Temperature Difference
R-CTRC	CO_2-based transcritical Rankine cycle with a regenerator

circuit between the exhaust gas and the working fluids [5,6], and adopting a duel loop bottoming ORC [7–9]. Unfortunately, the oil circuit makes extra exergy and energy losses, and the high-temperature organic fluids are mostly flammable, which may cause serious safety issues. Additionally, environmental issues still exist in many organic fluids, mainly concerning about the high GWP and ODP.

To overcome the drawbacks of ORCs used for the high temperature waste heat recovery, carbon dioxide (CO_2) based transcritical Rankine cycle (CTRC) system has been developed recently [10–15]. The CTRC has the same system configuration compared with the transcritical ORCs, only using CO_2 as the working fluid instead of organic fluids. CO_2 is a natural working fluid, which is environment-friendly, feasible, low-cost and safe. It fits well for recovering the high temperature exhaust gas of engines with no limitation of thermal decomposition temperature and safety, environmental issues, which result in the convenience of experiment and application of the CTRC for engine waste heat recovery. Moreover, the supercritical heat transfer process of the CTRC can achieve a better match between the exhaust gas and the working fluid, because it avoids evaporation in constant temperature. Inside the technological framework of thermal energy management, the performance of waste heat recovery can be improved through the CTRC.

Theoretical and experimental investigations are both contained in the study of the CTRC for engine waste heat recovery. Chen et al. [10] proposed different CO_2 bottoming systems for the exhaust recovery of vehicles, including the CTRC, CO_2 Brayton cycle and CO_2 combined cycle. Their results showed that the CTRC was more attractive, and about 20% of energy in the exhaust gas can be converted into work though a system optimization. Echogen Power Systems (EPS) company [11,12] in the USA has done preliminary tests of a 250 kW gas waste heat recovery system with the CTRC, which indicates the possibility of recovering the waste heat of engine exhaust gas with a wide temperature range from 200 °C to 540 °C. Mahmood et al. [13] studied the waste heat recovery on an 80 kW natural gas powered engine by the CTRC. The results showed that as much as 18 kW power could be generated. Meanwhile, there are some researches focusing on the performance comparison of aspects between the CTRC system and ORCs. The CTRC system is superior in heat transfer performance when compared with ORCs using R245fa [16], ethane [17], R32 [18] and R125 [19]; and superior to ORCs using R123, R245fa, R600a and R601 [20] in economic performance, but the CTRC is inferior in net power output and thermal efficiency [16–18,20,21].

Therefore, some modifications of the CTRC are proposed to improve net power output and thermal efficiency. Among the options, cycle configuration modification has been generally used. Adding a regenerator is one alternative effective way [22,23], generally used in various fields of waste heat recovery. Besides, another way is to add a preheater to adapt to two heat sources of engine [13,24], high-grade exhaust gas (200–900 °C) and low-grade engine coolant (60–100 °C). The low-grade engine coolant can be used to preheat working fluids based on the recovery of exhaust gas. The results in current literatures [6,25] show that exhaust gas and engine coolant can't be combined well for ORCs. However, it can be improved by the large specific heat capacity of supercritical CO_2 [24]. Hence, considering the above modifications,