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Experimental comparison between four CO_2-based transcritical Rankine cycle (CTRC) systems for engine waste heat recovery

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ABSTRACT

In order to recover waste heat from both exhaust gas and coolant water of engine, and improve system thermal efficiency, four CO_2-based transcritical Rankine cycle (CTRC) systems with kW-scale power output were constructed, including a basic CTRC (B-CTRC), a CTRC with a regenerator (R-CTRC), a CTRC with a coolant preheater (P-CTRC) and a CTRC with both the preheater and the regenerator (PR-CTRC). Experimental comparison between the four systems was presented based on an expansion valve, which can make system operate steadily and obtain the potential of net power output. Energy analysis, exergy analysis and cooling load analysis for the four systems were conducted at various pressure ratios. The results indicated that the PR-CTRC owned the highest potential of net power output, thermal efficiency and exergy efficiency, whose estimation reached up to 3.47 kW, 7.8% and 17.1%, respectively. In view of the linear fitting value at the same pressure ratio of 1.65, net power output, thermal efficiency and exergy efficiency of the PR-CTRC achieved increase of 100.6%, 69.6% and 79.5% versus that of the B-CTRC, respectively. Furthermore, the PR-CTRC required the lowest total cooling load jointly considering the engine and the CTRC system. The P-CTRC and the R-CTRC also had better thermodynamic performance than the B-CTRC did, but it was worse than that of the PR-CTRC. The preheater had more active effect on the power output, exergy efficiency and cooling load of the engine, and the regenerator contributed more to the thermal efficiency and cooling load of the CTRC. In summary, two main aspects of improvement for the engine were achieved by the PR-CTRC: thermal efficiency of the engine increased from 39.4% to 41.4% by the additional power output of bottoming system, and about 50% cooling load of the engine could be reduced and converted to preheat input of the CTRC system.

1. Introduction

Increasing the total fuel efficiency of engines has become a hot topic and attracted wide research, which contributes to saving fuel and reducing CO_2 emissions. Waste heat recovery technology hence becomes a promising and potential way to achieve a considerable increase of engine efficiency. According to typical operating parameters of engines [1,2], maximum efficiency of 32% and 42% was obtained by gasoline engine and diesel engine, respectively. The residual energy of fuel (above 50%) mainly converts into engine waste heats, especially in exhaust gas and engine coolant. Among waste heat recovery technologies, power cycles prove to be promising heat-to-power conversion methods, which have been attracting enormous research interests for their high operability, reliability and flexibility [3,4].

Currently, CO_2-based transcritical Rankine cycle (CTRC) has attracted more and more attention as a potential power cycle for engine waste heat recovery. From perspective of fluid property, carbon dioxide (CO_2) is a natural fluid with environment-friendly, non-flammable and non-corrosive properties, which causes less safety problem. Among the waste heats of engines, exhaust gas is the main recovery source with a great amount of energy and the high temperature grade, whose temperature can reach up to above 500 °C for diesel engine and above 700 °C for gasoline engine [5]. CO_2 shows favorable thermal stability when facing with high-temperature exhaust gas. Thus, direct heat transfer process between CO_2 and exhaust gas can realize and reduce energy and exergy loss due to better temperature match. However, it means a significant problem for plenty of Organic Rankine Cycle (ORC), which needs additional structure (e.g., intermediate oil cycle [6], intermediate steam cycle [7], high-loop steam power cycle [8]) or more stable but flammable high-temperature organic fluids (e.g., Alkanes [9], Siloxanes [10]) to match high-temperature exhaust gas.

From the perspective of system performance, CTRC shows better exchanger performance and economic performance in many comparative researches versus ORCs with R245fa [11], R32 [12], R125 [13], R123 [14] and so on. Small exchanger due to excellent heat transfer property of supercritical CO_2, and small turbine due to large energy

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Nomenclature

h	specific enthalpy (kJ/kg)
I	exergy loss (kW)
m	mass flow rate (kg/s)
P	pressure (MPa)
Power	power output (kW)
Q	heat flow rate (kW)
RD	relative difference (%)
t	temperature (°C)
Δt	temperature difference (°C)
U	utilization rate of waste heat (%)
V	volume flow rate (m^3/h)
W	work (kW)

Greek letters

η	efficiency

Subscripts

cond	condenser
c	cooling water
cool	cooling
cond	condenser
E	exergy
ec	engine coolant
est	estimation
f	working fluid
g	exhaust gas
gen	generator
gh	gas heater
max	maximum
min	minimum
net	net output
preh	preheater
prec	precooler
reg	regenerator
th	thermal
turb	turbine
c, 1–3	state point of cooling water
ec, 1–4	state point of engine coolant
g, 1–2	state point of exhaust gas
1–7	state point of CO_2
4, ideal	state points for the ideal case

Abbreviations

CTRC	CO_2-based transcritical Rankine cycle
EC	engine coolant
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
SWEP	Company name, a world-leading supplier of brazed plate heat exchangers

density of supercritical CO_2 and low expansion ratio, can be applied to CTRC system and meet the compact requirement of engine waste heat recovery. However, low thermal efficiency and low net power output are the main disadvantages of CTRC system with a basic configuration which is composed of gas heater, expander, condenser and pump [12–14]. It becomes significant to improve the thermodynamic performance of the basic CTRC, and configuration modification seems be an efficient way. At present, on the base of exhaust gas recovery in a basic configuration, addition of a preheater or a regenerator to basic configuration is the main choice of configuration modification for single loop CTRC system. The preheater and the regenerator increase CO_2 enthalpy of turbine inlet from the heat source outside and internal CTRC, respectively. Both of them have positive effect on the system power output and thermal efficiency.

Generally, preheater is special for engine waste heat recovery as engine owns various waste heats. Among them, engine coolant is the best preheat source with low grade temperature (less than 100 °C) and large amount of waste heat (about 1/3 of fuel energy) [1]. Engine coolant plays a role of heat dissipation in engine system. Thus, the preheat process not only improves the energy input of CO_2, but also reduces the cooling load of engine. Therefore, the key point is to maximize the utilization rate of engine coolant. An important result obtained by our group led by Shu [14] indicated that the CTRC had a better combined capability of exhaust gas and engine coolant compared with R123-based transcritical ORC. Utilization rate of both exhaust gas and engine coolant could obtain above 0.9 for the CTRC, but the R123-based transcritical ORC realized a little higher utilization rate of exhaust gas but a much lower utilization rate of engine coolant (less than 0.3). The weak recovery capability of engine coolant was also presented at other preheated ORC research for engine waste heat recovery [15,16]. If systems aim at achieving the complete use of exhaust gas and engine coolant simultaneously, a higher specific heat capacity is required within the narrow application temperature range of engine coolant than the wider application temperature range of exhaust gas. The specific heat capacity property of supercritical CO_2 exactly conforms to this condition, as the peak of specific heat capacity is located within the application temperature range of engine coolant. This good performance of supercritical CO_2 was also proved from the enthalpy perspective by Kim et al. [17] in a CTRC investigation for the combined use of high-grade and low-grade heat sources. In that study, preheated process was used as an optimization solution for the basic CTRC, which produced approximately 15% more power.

Compared with the preheater, the regenerator is more widespread for the CTRC system. Low pressure ratio between turbine's inlet and outlet in the CTRC system makes CO_2 with high temperature flow into condensation process. Thus, regenerator is widely used in the CTRC system. In the exhaust gas recovery study by Chen et al. [18], simulation results showed that the thermal efficiency of regenerated CTRC system became 0.19 and 0.31 after assuming 60% and 90% effectiveness for the regenerator, and realized great improvement relative to basic configuration with 0.08 thermal efficiency. Li et al. [19] concluded that the system with a regenerator could operate at a higher expander inlet pressure, higher heat source temperature and lower heat sink temperature compared with basic system. Autier et al. [20] conducted an optimization study of a CTRC for exhaust gas recovery of fishing boat's diesel engine, and concluded that the CTRC would have the highest efficiency with lower gas heater pressure after a regenerator was added to the system. The same conclusion was also illustrated in the research of low-grade waste heat recovery [21,22]. Therefore, it is valuable to add a regenerator to increase thermal efficiency and reduce optimal pressure of CTRC system.

Considering system optimization by adding a preheater or a regenerator, CTRC system can be divided into four configurations: basic CTRC (B-CTRC), CTRC with a preheater (P-CTRC), CTRC with a regenerator (R-CTRC), CTRC with both a preheater and a regenerator (PR-CTRC). It is necessary to conduct comparative study of the four