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Comparisons of system benefits and thermo-economics for exhaust energy recovery applied on a heavy-duty diesel engine and a light-duty vehicle gasoline engine

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ABSTRACT

Exhaust energy recovery system (EERS) based on Rankine cycle (RC) in internal combustion engines have been studied mainly on heavy-duty diesel engines (D) and light-duty vehicle gasoline engines (G), however, little information available on systematical comparisons and evaluations between the two applications, which is a particularly necessary summary for clarifying the differences. In this paper, the two particular systems are compared quantitatively using water, R141b, R123 and R245fa as working fluids. The influences of evaporating pressure, engine type and load on the system performances are analyzed with multi-objectives, including the thermal efficiency improvement, the reduced CO_2 emission, the total heat transfer area per net power output (*APP*), the electricity production cost (*EPC*) and the payback period (*PBP*). The results reveal that higher pressure and engine load would be attractive for better performances. R141b shows the best performances in system benefits for the D-EERS, while water exhibits the largest contributions in the G-EERS. Besides, water performs the best thermo-economics, and R245fa serves as the most uneconomical fluid. The D-EERS presents superior to the G-EERS in the economic applicability as well as much more CO_2 emission reductions, although with slightly lower thermal efficiency improvement, and only the D-EERS with water under the full load meets the economic demand. Therefore the EERS based on RC serve more applicable on the heavy-duty diesel engine, while it might be feasible for the light-duty vehicle gasoline engine as the state-of-the art technologies are developed in the future.

1. Introduction

Greenhouse effect and depleted petroleum supplies have urged the harsh demands on the fuel economy improvements of internal combustion engine (ICE). Therefore, waste heat recovery (WHR) technology based on Rankine cycle (RC) is getting revived and paid much attention in recent years. The ICE equipped with a RC system could have a considerable improvement by up to 10–15% in fuel consumption [1].

Reviewing the literatures in the past decades, most of the studies were aimed at the application to heavy-duty diesel engine trucks, ships, and generators, etc. due to the stable operations and high quantity of waste heat. Early in 1980s, Patel and Doyle [2] made a conceptual design study of compounding a long haul diesel truck engine with an organic RC system. DiNanno et al. [3,4] also tested an organic RC system compounded on a class 8 diesel engine with 288 brake horsepower. Recent examples using the RC for WHR can be found from the experimental researches conducted by Teng et al. [5–7], which demonstrated up to 20% of waste heat from the heavy-duty diesel engine may be recovered, making the efficiency for the hybrid energy system be over 50%. Hountalas et al. [8,9] provided theoretical simulations and experimental design of RC applied on a heavy-duty diesel engine used in long haul trucks to estimate the potential efficiency gain from its application and the attempts to resolve technical challenges such as system packaging and excess coolant heat rejection. Macián et al. [10] presented a methodology for the optimization of a bottoming cycle for recovering various waste heat sources from a heavy duty diesel engine. Other researches include the work of Shu et al. [11–13], who compared several dual-loop organic RC systems to explore the best combined system and working fluids for the maximum utilization of WHR from diesel engine.

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Nomenclature

a	specific amount (kg/(kW h))
A	overall heat transfer area (m^2)
APP	total heat transfer area per net power output (m^2/(kW))
C_{bm}	component cost ($/year)
Cc	system capital cost ($/year)
$CEPCI$	Chemical Engineering Plant Cost Index
Com	operation and management cost ($/year)
c_p	specific heat of exhaust gas (J/(kgK))
C_{pri}	average price of diesel or gasoline (¥/t)
CRF	capital recovery cost
C_t	temperature difference correction factor
d	diameter (m)
D	heavy-duty diesel engine
EERS	exhaust energy recovery system
EI	thermal efficiency improvement
EPC	electricity production cost ($/(kW h))
f	resistance coefficient
G	light-duty vehicle gasoline engine
h	specific enthalpy (kJ/kg)
i	interest rate
ICE	internal combustion engine
LMTD	logarithmic mean temperature difference
LT	system operation lifetime (year)
m	mass flow rate (kg/s)
M	amount (kg/year)
Nu	Nusselt number
p	pressure (MPa)
Pr	Prandtl number
PBP	payback period (year)
PPTD	pinch point temperature difference
Q	heat transfer rate (kW)
R	net return per year ($/year)
RC	Rankine cycle
Re	Reynolds number
t	overall operating time per year (h)
T	temperature (°C)
U	overall heat transfer coefficient (W/(m^2 K))
W	work (kW)
WHR	waste heat recovery
α	heat transfer coefficient (W/(m^2 K))
ε	correction factor
η	efficiency
ρ	density (kg/m^3)
λ	thermal conductivity coefficient (W/(mK))

Subscripts

c	condenser
cw	cooling water
e	evaporator
eng	engine
exh	exhaust gases
i	inner
l	liquid state
o	outer
p	pump
t	turbine
v	vapor state
w	working fluid
1–7	states points in the cycle
0	atmosphere

Alternatively, much attention has also been paid on gasoline engines based on the considerations of low thermal efficiency and high exhaust gases temperature for the kind of engines. Stem from 1990s, Oomori and Ogino [14] combined the evaporative engine cooling system and Rankine bottoming system in search for the application possibility of Rankine bottoming system to passenger cars. In this century, Chammas and Clodic [15] presented the advantages of a Rankine system on a 1.4 L spark ignition engine for a typical passenger car, with potential for improving the net fuel consumption by up to 32%. Ringler et al. [16,17] employed a dual RC system for gasoline passenger car application and have recently developed a dynamic model of the evaporator for the WHR system. Arias et al. [18] and Endo et al. [19] proposed novel WHR systems to achieve the maximum potentials on gasoline automotive vehicle. Analysis based on experiments of a light duty gasoline engine by Wang et al. [20] predicted that the maximum exhaust energy recovery system (EERS) efficiency can be up to 14% under high engine power condition and 3–8% under general vehicle operating conditions. Wang et al. [21] analyzed the potential of a dual loop organic RC within the gasoline engine's entire operating region, and found that the relative output power improves by from 14% to 16% in the peak effective thermal efficiency region to 50% in the small load region, and the absolute effective thermal efficiency increases by 3–6% throughout the engine's operating region. Peng et al. [22] examined integrated EERS for light duty gasoline vehicle and hybrid electrical vehicle in the improvement on the total power-train efficiency and net reduction of CO_2 emissions, indicating better economical benefits for the hybrid vehicle with EERS.

Reviewing those investigations above, WHR systems were applied and studied mainly on heavy-duty diesel engines and light-duty vehicle gasoline engines independently. However, little information available has been reported on systematical comparisons and evaluations between the two applications, which is a particularly necessary summary for clarifying the differences. Therefore, this paper provides quantitative comparisons through analyzing EERS applied on a typical heavy-duty diesel engine and a light-duty vehicle gasoline engine, using four attractive working fluids including water, R141b, R123 and R245fa, in order to identify the pros and cons for the two systems and offer general considerations for selections. The thermal efficiency improvement and the reduced CO_2 emission are chosen to be the objective functions to assess the system benefits. The total heat transfer area per net power output (*APP*), the electricity production cost (*EPC*) and the payback period (*PBP*) are examined from the view point of thermo-economics.

Table 1
Specifications for engines used in this investigation.

Parameters	Diesel engine	Gasoline engine
Bore (m)	0.126	0.0825
Stroke (m)	0.130	0.0842
Displacement (cm^3)	6000	1798
Compression ratio	17:1	9.5:1
Injection system	Common rail	Direct injection