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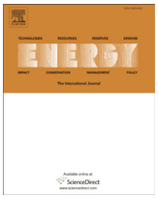

Energetic analysis of a novel vehicle power and cooling/heating cogeneration energy system using cascade cycles

Chen Yue [a, b, *], Dong Han [a], Wenhao Pu [a], Weifeng He [a]

[a] *Nanjing University of Aeronautics and Astronautics, Jiangsu Province Key Laboratory of Aerospace Power Systems, Nanjing 210016, China*
[b] *Department of Chemical & Biological Engineering, Northwestern University, Evanston, IL 60208, USA*

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A B S T R A C T

This study proposes and investigates a novel VCES (Vehicle power and cooling/heating Cogeneration Energy System), including a topping vehicle engine subsystem, and a bottoming waste-heat recovery subsystem which uses the zeotropic working fluid. The various grade exhaust and coolant waste-heat of the topping subsystem are cascade recovered by the bottoming subsystem, and slide-temperature thermal match in waste heat recovery heat exchangers and the condenser is considered also, obtaining power output and cooling/heating capacity. Based on the experimental data from an actual vehicle's energy demands and its waste-heat characteristics, the proposed VCES (vehicle cogeneration energy system) model is built and verified. Using ammonia-water as working fluid of the bottoming subsystem, integrated thermodynamic performances of the VCES are discussed through introducing three variables: an ambient temperature, the vehicle's velocity and the number of seated occupants. The influence of above three variables on the proposed VCES′ overall thermodynamic performance is analyzed by comparing it to a conventional VCES, and suitable operation conditions are recommended under cooling and heating conditions.

1. Introduction

Approximately 16% of humanity's energy use is consumed by transportation vehicles [1]. It is reported that the average fuel consumption of vehicles increases by 12–17% during regular commuting when incorporating the compression power consumption of the vehicle's AC (air conditioning) unit [2]. An engine using HCCI (homogenous charge compression ignition) or GDI (gasoline direct-injection) is the most commonly used driving equipment in transportation vehicles, and it is reported that a conventional vehicle GDI engine achieves a 30% thermal efficiency [3], but it is difficult to exceed a peak efficiency of 45% [4]. Except for the energy conversion to power, approximately 2/3 of the fuel's chemical energy is discharged to the ambient via exhaust, coolant and lubricating oil waste heat [5]. Improving the fuel thermal-energy utilization efficiency of a vehicle engine through WHR (waste-heat recovery) technology is therefore a valuable research direction that has achieved recent popularity [6].

The bottoming power generation cycle is considered a promising technology with which to recover various grade waste heats from vehicle engines [7–13]. Saidur et al. [8] and Wang et al. [9] presented reviews of WHR from ICE (internal combustion engines) using the Rankine cycle, discussing various systems and working fluids. Domingues et al. [10] evaluated the vehicle exhaust WHR potential using a Rankine cycle, showing the prominent increase of the ICE thermal efficiency and vehicle mechanical efficiencies by using the bottoming subcritical ORC (organic Rankine cycle) technologies with pure working fluid. Macian et al. [11] proposed a methodology for the optimization of the bottoming WHR cycles in vehicles, and two cases are analyzed to evaluate the preliminary energetic and technical feasibility of the bottoming WHR subcritical ORC in heavy duty diesel engines. Sprouse III and Depcik [12] primarily reviewed the selection and cycle expander and working fluid for the bottoming ORC of ICE exhaust WHR, and the some researches on bottoming exhaust WHR ORC for vehicles have been introduced. Horst et al. [13] studied the dynamic performance and energy saving potential of the bottoming WHR ORC for passenger car application.

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[*] Corresponding author. College of Energy & Power Engineering, Nanjing University of Aeronautics and Astronautics, No. 29 Yudao Street, Nanjing 210016, China. Tel./fax: +86 02584892201.
E-mail address: yuechen025@gmail.com (C. Yue).

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Nomenclature

a	static convective heat-transfer coefficient
A	effective heat-transfer area, m^2
b	dynamic convective heat-transfer factor
B	bore, mm
c	gear ratio
cv	specific heat capacity at constant volume, kJ/(kg.K)
cp	isobaric specific heat capacity, kJ/(kg.K)
d	wheel diameter, m
h	specific enthalpy or heat-transfer coefficient, kJ/kg or kJ/(kg.K)
k	adiabatic index
m	mass flow rate, kg/s
M	molar mass, kg/kmol
n	engine rotational speed, RPM
N_p	number of person
p	pressure, kPa
P	power output, kW
Q	thermal energy, kW
Q_0	overall fuel lower heating value, kW
Q_1	exhaust heat recovered, kW
Q_2	condensing load of VCR, kW
Q_3	cooling/heating demand, kW
Q_4	discharged heat of condenser, kW
q	heating value of fuel, kJ/kg
R	gas constant, kJ/(kmol.K)
S	stroke, mm
T	temperature, K
v	specific volume, m^3/kg
V	volume flow rate, m^3/s
x	mass fraction in mixtures

Symbols

$\triangle t$	minimal temperature difference in heat exchanger, K
$\triangle \eta$	efficiency improvement, %
β	expansion ratio during expansion stroke
γ	air to fuel ratio
η	efficiency, %
π	compression ratio during compression stroke
ρ	density, kg/m^3
τ	number of crankshaft revolutions

Subscripts

0,1,2,…	state point
a	air
C	compressor/condenser
cl	coolant
compression	compression stroke
disp	displacement volume
eg	exhaust gases
expansion	expansion stroke
fuel	fuel
hg	heat gained
L	heat loss
ICE	internal combustion engine
LHV	lower heating value
Loss	thermal energy loss
MEP	mean effective pressure
net	net work
Np	occupant number
Re	refrigerant
T	turbine
tot	total heat-transfer coefficient
V	volume
wf	working fluid
WHR	WHR subsystem

Abbreviations

AC	air conditioning unit
GDI	gasoline direct-injection
HCCI	homogenous charge compression ignition
ICE	internal combustion engine
ORC	organic Rankine cycle
WHR	waste-heat recovery
VCR	vapor compression refrigeration
VCES	vehicle cogeneration energy system

Many investigations on the combination of bottoming cycles and topping ICE were performed [14–27]. Srinivasan et al. [14] examined the exhaust WHR potential of a dual-fuel ICE using a subcritical ORC (organic Rankine cycle), with results showing that the fuel thermal utilization efficiency was improved by 7% and the specific emissions (NO_x and CO_2) were decreased by 18%. Clemente et al. [15] conducted an exergetic analysis of ORCs with scroll expanders for cogenerative applications, and their results confirmed the feasibility of a small-scale heating and power (CHP) combined system using subcritical ORC technologies. Bombarda et al. [16] conducted a thermodynamic performance comparison between Kalina and subcritical ORCs for diesel engine WHR, showing that thermal efficiencies of the bottoming Kalina and ORC were both over 17%. Tian et al. [17] proposed a subcritical ORC system for ICE exhaust WHR and conducted a techno-economic analysis based on various working fluids. He et al. [18] proposed a combination of a subcritical ORC and a Kalina cycle, conducting a thermodynamic performance analysis of an engine's WHR by considering the various waste-heat grade characteristics of the exhaust, coolant and lubricating oil. Boretti et al. [19] studied energy saving of a bottoming subcritical ORC based on a naturally aspirated gasoline engine, and the results indicated that the maximum overall fuel efficiency was improved by 8.2%. Katsanos et al. [20] conducted a fuel utilization efficiency comparison of a heavy-duty truck diesel engine with an exhaust WHR subcritical ORC when considering water and R245fa as working fluids. Duparchy et al. [21] analyzed the thermodynamic performance of a bottoming subcritical ORC for hybrid vehicles based an engine performance map. Shu et al. [22] proposed a new dual-loop ORC to recover waste-heat from exhaust and coolant that included both the subcritical–subcritical ORC and subcritical-transcritical ORC configurations. The influence of working fluid selection was also included in their study. Liang et al. [23] proposed a novel electricity and cooling cogeneration system containing a subcritical ORC and an absorption refrigeration cycle to recover the exhaust heat from marine engines aboard ships. Zhang et al. [24] designed a regenerative subcritical ORC using zeotropic mixture as working fluid to recover the diesel engine exhaust heat, studying the influence of the intermediate pressure on overall thermal performance. Vaja et al. [25] studied the WHR potential of a bottoming ORC with a topping ICE considering three working fluids and three cycle setups: a simple cycle that used only engine exhaust as a heat source, a simple cycle utilizing exhaust and coolant, and a regenerated cycle. Chen et al. [26] reviewed the use of the ORC for the conversion of low-grade

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