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Conceptual design, optimization, and assessment of a hybrid Otto-Stirling engine/cooler for recovering the thermal energy of the exhaust gasses for automotive applications

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ABSTRACT

The design of a combined Otto-Stirling system with the aim of simultaneous production of power and cooling using the waste energy of exhaust gases is presented. The internal combustion (IC) engine is modeled using a previously developed analytical thermal model. The Stirling engine and cooler are modeled using a new developed second-order thermal model called modified CAFS model. The modified CAFS model predicts the thermal efficiency with 2.74% relative error and output power with 12.27% error. The final thermal model of the hybrid Stirling-Otto engine is employed to design the hybrid system in two scenarios. In one scenario, it is assumed that the IC engine has a bottoming Stirling engine. While in the other scenario, in addition to the bottoming Stirling engine, a Stirling cooler is employed as a non-CFC alternative for cars' A/C systems. Both Stirling engine and cooler of two scenarios are optimized for highest power generation, heat recovery, and coefficient of performance. Two scenarios are assessed based on the fuel saving, emission reduction, and economic aspects. It is seen that in the best scenario, CO2 emission and fuel consumption will decrease by 27.6% and 15.3%, respectively.

1. Introduction

Two important consequences of the industrialization are enhanced global warming and progressive increase in the oil price. Reducing fossil-fuel consumption would lead to reduced environmental pollution and fuel expenses. Vehicles are good candidates for improvement, since their engines' efficiencies are normally lower than 35% which means they dissipate about two third of the energy. Moreover, the air-conditioning system in vehicles is another fuel consumer that uses CFCs as refrigerant whose GWP in a 20-years horizon is 3400 times more than the corresponding effect of carbon dioxide [1]. Therefore, improving the power production and cooling process, it is possible to make an important stride in reducing fuel consumption and respective environmental impact. One of the existing methods of increasing thermal efficiency is heat recovery. Using the initially wasted thermal energy for power production and cooling is an attractive idea. Different technologies, including the usage of Rankine cycles systems, thermoelectric energy generators, thermoacoustic systems, turbo-compound (electrical and mechanical) systems, thermophotovoltaic systems, and Joule cycles have been suggested for recovering the thermal energy of exhaust gases. Various technologies for improving the thermal efficiency of ICEs through the recovering the thermal energy of exhaust gases or the usage of hybrid engines was evaluated and assessed by Shabashevic et al. [2]. In addition, the impacts of these technologies on fuel consumption of a passenger car in a normalized driving cycle were compared by Legros et al. [3]. In the context of recovering the waste energy in IC engines, several works focused on Rankine cycle as a bottoming cycle. Badami et al. [4] studied the usage of the Rankine cycle for the heat recovery of exhaust gases. In the Ph.D. thesis conducted by Ali [5], the implications of combining a Rankine steam cycle with a turbocharged Otto engine was examined experimentally and 7.45% increase in the thermal efficiency and a fuel saving of 6.93% at 2500 RPM was obtained. In addition, through the use of steam turbo-charging, the output power of the engine was increased by 35.00% that led to 13.73% increase in power density of the proposed engine. BMW's turbo-steamer was designed to produce power using available thermal energy in a vehicle. According to the company's claim, this system would generate 10 kW power and save fuel up to 15% in the case that the turbo-steamer system was employed on a four-cylinder engine with 1.8-L capacity [6]. Because ORCs are suited to efficiently exploit low grade thermal energy sources, the usage of these cycles instead of conventional Rankine cycle was attentional by many researchers [7–12]. In these studies, different

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Nomenclature

A	area (m^2)
B	a constant
A_T	throat area (m^2)
a	constant
C	Cost or a constant
CAFS	combined adiabatic and finite-speed model
C_D	discharge coefficient
C_f	frictional pressure coefficient
c	sound speed ($m{\cdot}s^{-1}$)
c_p	specific heat at constant pressure ($kJ{\cdot}kg^{-1}{\cdot}K^{-1}$)
c_v	specific heat at constant volume ($kJ{\cdot}kg^{-1}{\cdot}K^{-1}$)
D	diameter (m)
D_H	hydraulic diameter (m)
d	discount rate
dis	discount rate
F	Future value of a cost
f_r	frequency (Hz)
Gs	solar irradiation ($W{\cdot}m^{-2}$)
H	specific enthalpy ($kJ{\cdot}kg^{-1}$)
h	convective heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
inf	Inflation rate
J	clearance (mm)
k	conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
L	length (m)
m	mass (kg)
NTU	Number of the transfer unit
n_v	number of valves
P	pressure (kPa)
Pr	Prandtl number
PW	present worth
Q	thermal energy (kJ)
R	conductive thermal resistance ($K{\cdot}m{\cdot}W^{-1}$)
R_g	gas constant ($kJ{\cdot}kg^{-1}. K^{-1}$)
R_e	Reynolds number
R_H	hydraulic radius (m)
r_v	compression ratio
St	Stanton number
s	stroke (m)
T	temperature (K)
t	time (s)
th	thickness (m)
U	overall heat transfer coefficient ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
u	gas velocity ($m{\cdot}s^{-1}$)
V	volume (m^3)
W	work energy (kJ)
w	piston speed ($m{\cdot}s^{-1}$)

Greek symbols

α_s	absorbed solar irradiation fraction
γ	specific heats ratio
ΔP	pressure loss (kPa)
ε	regenerator effectiveness
μ	viscosity (Pa·s)
ν	car's velocity ($m{\cdot}s^{-1}$)
ρ	density ($kg{\cdot}m^{-3}$)

Subscripts

0	reference or environmental condition
ac	air conditioner
avg	average
amb.	ambient
bd	blowdown
CAFS	related to CAFS model
c	compression space
d	displacer
disp.	displacement
e	expansion space
eng.	related to the engine
ex	exhaust
f	friction
FST	finite-speed thermodynamics
h	heater space
he	the interface of heater and expansion spaces
g	gas
i	instantaneous
c	compression space
ck	the interface of compression and cooler spaces
in	inside
ini	initial
irr	irreversible
k	cooler (kooler)
kr	the interface of cooler and regenerator spaces
leak	leakage
m	mean
o	outside
obj.	objects
p	piston
Q	heat loss
r	regenerator
rh	the interface of regenerator and heater spaces
rev	reversible
shut	shuttle effect
T	Properties at a temperature equal to T
th	thermodynamic cycle
thrott	throttling
vent.	ventilation
w	wall
wh	heater's wall
wk	cooler's wall

aspects of the bottoming organic Rankine cycle including its performance, the effect of working fluid, technical aspects of the usage, and the usage of a new configuration of the bottoming Rankine cycle were addressed.

The usage of the electric turbo compounds (ETC), a technology for recovering the thermal energy from the exhaust gases in ICEs was numerically investigated by Pasini et al. [13]. They concluded that the ETC does not improve the fuel economy of small vehicles, especially when it is used in driving cycles of urban areas; however, this technology is effective for large vehicles, particularly at extra-urban driving cycles. Another possible alternative for recovering the waste energy of the exhaust flow of ICEs would be Stirling systems. Stirling engines have been a matter of interest among scientists and engineers due to their high theoretical power output, efficiency, and compactness. The main idea in the present work is to evaluate the possibility of combining ICEs with Stirling engines and Stirling coolers with the aim of increasing the thermal efficiency and replacing the vapor compression cooling system. The usage of Stirling machines in combined cycles drew attention in the 1980s. For example, in 1985, Carqvist and Kamo [14] suggested combined diesel-Stirling engine whose efficiency could reach up to 60%. In 1989, Benvenuto et al. [15] introduced combined Rankine-Stirling and Brayton-Stirling cycles and showed that those cycles