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Analysis of vehicle exhaust waste heat recovery potential using a Rankine cycle

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ABSTRACT

This study evaluates the vehicle exhaust WHR (waste heat recovery) potential using a RC (Rankine cycle). To this end, both a RC thermodynamic model and a heat exchanger model have been developed. Both models use as input, experimental data obtained from a vehicle tested on a chassis dynamometer. The thermodynamic analysis was performed for water, R123 and R245fa and revealed the advantage of using water as the working fluid in applications of thermal recovery from exhaust gases of vehicles equipped with a spark-ignition engine. Moreover, the heat exchanger effectiveness for the organic working fluids R123 and R245fa is higher than that for the water and, consequently, they can also be considered appropriate for use in vehicle WHR applications through RCs when the exhaust gas temperatures are relatively low. For an ideal heat exchanger, the simulations revealed increases in the internal combustion engine thermal and vehicle mechanical efficiencies of 1.4%–3.52% and 10.16%–15.95%, respectively, while for a shell and tube heat exchanger, the simulations showed an increase of 0.85%–1.2% in the thermal efficiency and an increase of 2.64%–6.96% in the mechanical efficiency for an evaporating pressure of 2 MPa. The results confirm the advantages of using the thermal energy contained in the vehicle exhaust gases through RCs. Furthermore, the present analysis demonstrates that improved evaporator designs and appropriate expander devices allowing for higher evaporating pressures are required to obtain the maximum WHR potential from vehicle RC systems.

1. Introduction

ICEs (Internal combustion engines) are the major source of motive power in the world, and this is expected to continue for some decades. Greenhouse effects and depleted petroleum supplies are crucial issues that the developed world's economies are facing. Because of this, governments in industrialized countries have introduced strict regulations for ICE emissions and fuel economy standards. In the last two decades, manufacturers have improved significantly ICE efficiencies by applying a number of new technologies [1]. In recognition of the need to further reduce vehicle exhaust pollutant emissions (CO, NO_x, hydrocarbons and particulate matter) and, more recently, also CO_2 emissions, there has been a lot of interest in the development of cleaner and more efficient vehicle powertrains [2].

In ICEs only about 1/3 of the fuel combustion energy is converted into useful work to drive the vehicle and its accessory loads. The remainder is engine waste heat dissipated by the engine exhaust system, coolant system, and convection as well as radiation from the engine block [3]. Nearly 40% of the heat energy is wasted with the engine exhaust gases [4]. If the waste heat of an ICE can be recovered, the engine efficiency will be improved [3]. Furthermore, global warming will be decreased [5].

To increase the ICEs thermal efficiency and to reduce CO_2 emissions, different WHR (waste heat recovery) techniques were recently proposed [1–10]. Among the existing WHR techniques, the most important are the ETC (electrical turbo-compounding), the MTC (mechanical turbo-compounding), the TIGERS (turbo-generator integrated gas energy recovery system), the TEG (thermo-electric generator) and the RC (Rankine cycle) [6,7].

A number of studies [e.g., [1–3, 5,6]] demonstrate that the RC or the ORC (organic Rankine cycle) has a high WHR potential in automotive applications. The RC is based on the steam generation in a secondary circuit, which represents an indirect method of WHR. This technique has advantages compared with the so-called direct WHR techniques (e.g., ETC, MTC and TIGERS) that use a power turbine fitted to the vehicle exhaust, which has a much higher impact on the engine pumping losses. In addition, a RC allows for high waste energy utilization and it is cheaper than other WHR techniques such as thermo-electric generators [5].

The choice of the working fluid to be used in the RC depends on a number of factors, namely, thermodynamic, environmental,

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Nomenclature

A	area [m^2]
A/F	air/fuel ratio
b	long side of a rectangular cross section [m]
c_p	heat capacity [kJ kg^{-1} K^{-1}]
d	diameter [m]
D_h	hydraulic diameter [m]
$\dot{E}$	exergy flow rate [kW]
f	Darcy friction factor
F	imposed load [N]
h	specific enthalpy [kJ kg^{-1}]; heat transfer coefficient [W m^{-2} K^{-1}]
$\dot{I}$	exergy destruction rate [kW]
k	thermal conductivity coefficient [W m^{-1} K^{-1}]
L	evaporator tube length [m]
LHV	low heating value [MJ kg^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
N	engine speed [rpm]
N_t	tubes number
Nu	Nusselt number
p	pressure [Pa]
P	vehicle effective power [kW]
Pr	Prandtl number
$\dot{Q}$	heat rate [kW]
R_d	fouling factors [m^2 K W^{-1}]
Re	Reynolds number
T	temperature [K]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]
v	specific volume [m^3 kg^{-1}]
V	vehicle speed [km h^{-1}]
$\dot{W}$	power [kW]

Greek symbols

α^*	aspect ratio of rectangular ducts, ratio of a small to large side length
β	surface area density [m^2 m^{-3}]
δ	distance between tubes [m]
Δp	pressure drop [Pa]
ε	heat exchanger effectiveness
η	efficiency
μ	dynamic viscosity [N s m^{-2}]
ρ	density [kg m^{-3}]

Subscripts

o	initial
1,2,3,4	Rankine cycle process
amb	ambient
c	thermodynamic cycle
cond	condensation
crit	critical
e	effective
evap	evaporating
exp	expansion
ext	external
f	working fluid
g	exhaust gases
h	hydraulic
i	internal
in	inlet
m	material
out	outlet
p	pump
pp	pinch-point
pump	pumping
s	isentropic
t	turbine
w	wall

Superscripts

m	viscosity ratio exponent

Abbreviations

BMEP	break mean effective pressure
EGR	exhaust gas recirculation
ETC	electrical turbo-compounding
HCFC	hydrochlorofluorocarbons
HFC	hydrofluorocarbons
ICE	internal combustion engine
MTC	mechanical turbo-compounding
NTU	number of transfer units
ORC	organic Rankine cycle
PPTD	pinch-point temperature difference
RC	Rankine cycle
TEG	thermo-electric generator
TIGERS	turbo-generator integrated gas energy recovery system
TWC	three way catalyst
WHR	waste heat recovery

safety, process-related and economic issues. In particular, when implementing such a system on a moving vehicle with live occupants, the choice must consider worse case scenarios like leakages or crashes. On that event the fluid must be harmless to the vehicle occupants. For vehicle applications, the low flammability level is a major concern. Hence, alcohols and hydrocarbons are arguably not the best candidates, in spite of their good thermodynamic efficiencies. Instead, refrigerants, already used in air conditioning systems, are usually good candidates. The refrigerants (e.g., R245fa) are widely used in ORC applications because of their good heat transfer properties, excellent thermal stability and low viscosity. They are generally safe (non-flammable) and compatible with most materials. Under typical low temperature ambient conditions they do not freeze, which is a major concern with water. However, the current generation of refrigerants called HFCs (hydroflurocarbons) has a high global warming potential (100-year time horizon) – 950–1070 for R245fa–, which means that their use could be limited or banned in the near future.

Various working fluids have been proposed for RC WHR applications. Saleh et al. [11] investigated 31 pure component working fluids for low-temperature ORCs. Lai et al. [12] investigated several pure working fluids (alkanes, aromates and linear siloxanes) for high-temperature ORCs. Yamamoto et al. [13] evaluated the optimum operating conditions of an ORC comparing HCFC (hydrochlorofluorocarbon)-123 and water as working fluids. Ringler et al. [14] examined two kinds of RCs for WHR from gasoline ICEs using water and ethanol as working fluids. Chammas and Clodic [15] compared the performance of water, R245ca and isopentane as RC working fluids in hybrid vehicles.

Since RCs generate additional power without requiring extra fuel, both the specific fuel consumption and the pollutant emissions of the vehicle are reduced [8,9]. The performance analysis of