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On the limiting factors of the waste heat recovery via ORC-based power units for on-the-road transportation sector

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ABSTRACT

Among the wide technological opportunities to reduce CO_2 emissions in the transportation sector, Waste Heat Recovery (WHR), done by Organic Rankine Cycle (ORC) power units, was subject of a great scientific interest. However, several complications apply for an on-board operation and management, which reduce its real benefit in terms of net fuel consumption reduction. Weight increase, encumbrances, engine backpressure, intrinsic off design operating conditions are all negative aspects which should be still solved.

In this paper, the interest is focused on the limiting factors of an ORC-based unit operating on board: engine backpressure due to Heat Recovery Vapor Generator (HRVG) presence, surface of the condenser and additional weight. All these aspects behave as limiting factors of the WHR. Considering the mechanical power produced by the unit as a desired input value, the paper discusses the HRVG and condenser sizing as a function of engine backpressure, weight increase and vehicle frontal area required by the condenser.

The engine considered was an IVECO F1C turbocharged diesel engine and the reference vehicle was a light duty one. Experimental data have been used for gas temperature and flow rates. The paper considers also the possible presence of an internal regeneration within the ORC which increases plant efficiency (reducing the dimensions of the HRVG and condenser) but introduces an additional heat exchanger. A correlation between weight of the heat exchangers and condenser frontal area as a function of the mechanical power recovered has been presented, without and with the regeneration stage.

1. Introduction

Exhaust heat recovery from internal combustion engines (ICEs) is one of the most studied technologies in order to reduce emissions and fuel consumption in the transportation sector. This recovery can be done directly: using secondary turbines that converts directly exhaust enthalpy in useful work [1]; considering an inverted Brayton cycle configuration [2]; or by thermoelectric generators (TEGs), which recently reached greater efficiencies producing a very low engine impact [3,4]. However, the most considered solution makes reference to an indirect recovery: power units in which the thermal energy is transferred to a working fluid which follows a sequence of cyclic thermodynamic transformations.

This approach has been widely investigated in literature [5,6] and different cycles have been proposed [7,8]. Rankine cycle surely demonstrated to be the most promising [9], working on fluids having suitable operating temperatures for the vehicular application. Normally adopted fluids have an organic nature, especially those with low global warming and ozone depletion potentials: R1233zd(E) seems to be the most considered one [10,11] as a substitute of the widely exploited R245fa [12,13]. Its potentiality in mixtures with other fluids has also been investigated demonstrating a slightly increased performance [14].

While ORC units are almost conventional for large applications, they still meet several difficulties on a smaller scale, especially within the transportation sector:

(a) recovered energy should have a final use on-board: the mechanical power recovered can be used as it is, mechanically coupling ORC prime mover with ICE crankshaft, or it can be converted into DC electrical power and stored in a battery. In this latter case, additional energy losses are introduced [15];
(b) the weight of the ORC-based power units is an important issue: especially for light duty and passenger cars applications, where the higher fuel consumption due to the extra-weight on board could be relevant. On the other hand, in high heavy duty and off road vehicles, weight increase could not have a significant influence on propulsive power;
(c) the presence of the Heat Recovery Vapour Generator (HRVG) on the

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Nomenclature

Symbol

η_0	air side heat transfer area efficiency (condenser) –
h	convective heat transfer coefficient [kW/m^2 K]
ρ	density [kg/m^3]
dL	discretization length [m]
dP	pressure drop mbar
η	efficiency –
H	enthalpy [kJ/kg]
d	equivalent diameter [m]
v	fluid velocity [m/s]
A	heat exchange area [m^2]
δ	heat exchanger wall thickness [m]
F	heat transfer correction factor –
$\dot{I}$	irreversibilities [kW]
i	i-th heat transfer zone
$\dot{m}$	mass flow rate [kg/s]
U	overall heat transfer coefficient [kW/m^2 K]
p	pressure [Pa]
T	temperature [K]
k	thermal conductivity [kW/m K]
Q	thermal power [kW]
P_u	useful power [kW]
L_u	specific work [kJ/kg]
W	weight [kg]

Subscript

1	Rankine cycle point 1
2	Rankine cycle point 2
3	Rankine cycle point 3
4	Rankine cycle point 4
2s	cycle point 2s after regeneration
4s	cycle point 4s after regeneration
air	external air
ad, is	adiabatic-isentropic
crit	critical
exp	expander
hs	hot source
HX	heat exchanger
In	inlet
m	mechanical
out	outlet
ov	overall
PP	pinch point
reg	regeneration
sh	superheating
vap	vaporization
vol	volumetric
w	heat exchanger wall
wf	working fluid

Acronym

A/C	cabin air conditioning
ESC	European Steady Cycle
GWP	global warming potential
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefine
HRVG	Heat Recovery Vapor Generator
ICE	Internal combustion engine
LMDT	Logarithmic mean difference temperature
ORC	Organic Rankine Cycle
TEG	Thermo-Electric Generator

exhaust gases duct increases engine backpressure: this leads to an extra consumption of the engine and to the need for a re-calibration of the ICE. All these issues require a dedicated attention for turbocharged engines [16];

(d) ORC cold source on board represents an additional issue: its condenser, in fact, may be refrigerated by external air, by ICE coolant or through a dedicated liquid. In the first case, the condenser behaves like a secondary radiator and its dimensions and frontal area occupation may become relevant. In the second and third cases, the use of a liquid as coolant brings to a significant downsizing of the condenser, but subsequently the coolant has to be cooled by external air in an additional radiator [17,18];

(e) ORC hot source strongly varies during ICE operation due to the correspondent variations in ICE exhaust gas flow rate and temperature. Moreover, air side condenser conditions vary as well depending on actual vehicle speed. This means that the off design of the HRVG and condenser is very frequent; so that the choice of an ICE working point to size the ORC is still an open issue. Expander flexibility in off design conditions depends on the machine type (dynamic or volumetric). Control strategies have been developed as well [19,20] in this regard, but there is still room for improvement for a simple, safe, low cost and robust control.

All these considered, due to this importance, HRVG design received great attention in literature. Plate heat exchangers have been investigated for their compactness and the expected great heat transfer coefficients [21], but they have high pressure drops with detrimental effects both at the organic fluid and exhaust gas sides [22]: in fact, in the first case a reduction of the heat transfer is produced, while in the second case engine backpressure is increased. Shell and tube heat exchangers seem to be a good compromise between heat transfer efficiency, pressure drops [23], simplicity and cost [24,25], particularly those equipped by finned tubes [26]. Novel solutions are also possible integrating a radiator type heat exchanger inside a shell, further reducing pressure losses at the gas side (reducing engine back pressure) and increasing heat transfer performances.

Condenser design also gained literature attention: plate heat exchangers are used for steady applications and they are certainly suitable when the coolant is liquid [27]. In mobile applications, if a liquid/air exchanger is always required, plate tubes heat exchangers seem to be the best choice [28], [29]. This produces an additional use of vehicle frontal area which may not always available due to the aerodynamic constraints that vehicle has to face (ICE radiator, air conditioning system, charge air cooling, etc.).

Literature is wide on ORC systems, but few works about ICE vehicular applications. In fact, it mainly focuses on ORC performance within research labs, where working conditions as well as physical and aerodynamical constraints are normally steady quite different from those encountered on-board. Due to this, literature does not focus on potential ORC drawbacks produced by increased engine backpressure (produced by the HRVG), vehicle weight and frontal area requirements. All of them produce a correspondent increase on fuel consumption which is normally neglected in literature when estimating net power recovered by ORC. All these aspects should indeed be taken into account since the very beginning while optimizing the design of the ORC unit.

The paper discusses the relationship between the desired recovered mechanical power (seen as an input target) and the dimensions of the heat exchangers of the ORC power unit. So, this work aims to recuperate the lack in literature, introducing the constraints present on board (cold temperature source, weight increase, backpressure effect on