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Potential for exhaust gas energy recovery in a diesel passenger car under European driving cycle

Andrés F. Agudelo [a], Reyes García-Contreras [b], John R. Agudelo [a], Octavio Armas [b,*]

[a] Mechanical Engineering Department, Universidad de Antioquia, Medellín, Colombia
[b] Escuela de Ingeniería Industrial de Toledo, Universidad de Castilla-La Mancha, Toledo, Spain

HIGHLIGHTS

- Potential of waste thermal energy recovery from a diesel passenger car was evaluated.
- Tests were carried out following the NEDC at ambient temperatures of −7 °C and 20 °C.
- Thermal conditions of the gas were characterized at different points on the exhaust system.
- Significant differences on recovery potential were found by energy and exergy analyses.
- Feasible recovery potential had a peak value of 6% of the exergy supplied by fuel.

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ABSTRACT

This work addresses the potential for waste energy recovery from exhaust gases in a diesel passenger car mounted in a chassis dynamometer. The New European Driving Cycle was followed, while recording relevant operating variables. Tests were performed under three temperature conditions, and exergy analysis was included to find the potential of exhaust gases to produce useful work at six points in the exhaust system. Results include mean temperature at each point, as well as the energy quality index, which was lower than 33%, meaning that less than one-third of the energy of exhaust gases can be converted into useful work in a recovery system. In general, the highest exergy losses were found in the muffler. Although the greatest recovery potential corresponds to the highest temperature of gases, environmental regulations for vehicles restrict waste energy recovery to be performed downstream after-treatment devices, which, in the present work, was the outlet of the diesel particle filter. Temperature of gases at this location varied in the range 115–320 °C, and potential fuel saving varied between 8% and 19% for the complete driving cycle.

1. Introduction

World industry is challenged by primary energy availability and environmental concerns, given that about 80% of the world's energy comes from the combustion of coal, oil, and natural gas [1,2]. The European Commission adopted a target of limiting anthropogenic global warming to 2 °C above preindustrial levels, which implies emission reductions of greenhouse gases of near 50% by 2050, relative to 1990 levels [3]. Energy efficiency is of capital importance among the strategies for mitigating carbon emissions, given its potential contribution to the reduction of growth in energy demand and the consequent reduction of pollutant emissions [4–6]. In particular, transport is fundamental for welfare and economic development of a society, and it represents a significant share in the energy consumption of nations, as well as a major concern in regard to environmental pollution [7–9]. In this context, the search for improvements in energy efficiency of passenger cars is undeniable [10–13], given the great number of cars in urban areas [7,8,14]. In this direction, Euro regulations aim to reach a CO_2 emissions target of 95 g/km by 2021 and 68 g/km by 2025 for passenger cars and light duty vehicles (through reduction of fuel consumption) [12].

Abbreviations: DOC, diesel oxidation catalyst; DPF, diesel particle filter; EGR, exhaust gas recirculation; ICE, internal combustion engine; NEDC, new European driving cycle; ORC, organic rankine cycle; PFS, potential fuel savings; PM, particulate matter; SI, spark ignition.

* Corresponding author at: Escuela de Ingeniería Industrial de Toledo, Universidad de Castilla-La Mancha, Av. Carlos III s/n., Real Fábrica de Armas, 45071 Toledo, Spain.

E-mail address: octavio.armas@uclm.es (O. Armas).

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Nomenclature

a	coefficient for the calculation of specific heat
c_p	specific heat (J/kg K)
e	specific exergy (J/kg)
E	exergy (J)
$\dot{E}$	exergy rate (W)
F	fuel/air ratio
Fe	stoichiometric fuel/air ratio
Fr	fuel/air equivalence ratio
g	acceleration of gravity (m/s^2)
h	specific enthalpy (J/kg)
H	enthalpy–energy (J)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (kPa)
R	gas constant (J/kg K)
s	specific entropy (J/kg K)
t	time (s)
T	temperature (K)
V	speed (m/s)
Y	mass fraction
Z	elevation from ground level (m)

Subscripts

0	dead state conditions, initial conditions
a	air
b	burned gases (combustion products)
CV	control volume
d	destruction (exergy)
f	final conditions
F	fuel
g	exhaust gases
i	location of measurement points in the exhaust system
j	constant for calculation of properties
k	generic component
$Loss$	losses in the components
m	mean (time average)
Q	heat transfer
W	work

Superscripts

ch	chemical (exergy)
F	fuel

Greek characters

δ	exergy to energy ratio
ε	ratio of exergy of the gases to that supplied with fuel
Δ	difference

Since a typical passenger car uses about 35% of the energy available in the fuel [10,15–17], there is a potential for energy saving if part of the heat losses from cooling and exhaust systems [9] is recovered. In diesel engines, about 30% of fuel energy is wasted with exhaust gases [16,18–27]. There are several feasible alternatives to recover energy from the exhaust. The most promising are the production of mechanical power and electricity by Rankine cycles and thermoelectric generators, respectively [9,11,19,23,25,28–32]. Unfortunately, heat recovery systems might increase fuel consumption, mainly due to back pressure in the exhaust [12,33]. Rankine cycles are more suitable for large vehicles, such as buses and trucks where there is a higher absolute energy potential, and the additional weight and space required are less critical. The study of Rankine cycle technology to recover exhaust energy in diesel engines dates back to beginning of 1970 decade [11,13,19]. This technology requires complex control and is not well suited for transient operation [33]. Reported improvements in fuel consumption by using Rankine cycles vary significantly, in the range 1–16% [11–13,18,19,21,25,34,35], depending on the highest temperature of the cycle and on engine operating conditions. The higher the temperature of gases and engine load, the better the impact of this technology on fuel economy [13]. Thermoelectric generators (TEG) are a promising technology despite their low efficiency compared to conventional power cycles, due to their small weight and size, low maintenance costs, silent operation and high reliability [9,11,26,36–40]. A limitation for the implementation of TEG in passenger cars is the bigger radiator needed to dissipate the additional low temperature heat flow [11]. It is estimated that this technology could drive to a reduction of about 5% in fuel consumption, which might be significantly higher with the use of more advanced thermoelectric materials [11].

Most reported energy recovery studies are carried out under steady state engine conditions [10,12,15,17,19,27,34,41–43], which are not representative of real driving conditions [16]. The final design of the recovery system depends heavily on the actual amount and variability of energy flows [24]. Some works use the new European driving cycle (NEDC) to simulate engine operation [33,44], or to obtain steady engine operation points [16], finding fuel savings in the range of 1–4% depending on the recovery technology employed. Fuel savings are estimated to increase significantly for steady highway driving [44]. Location of a recovery system in the exhaust system of a vehicle is relevant, given that heat transfer may affect the operation of pollutant emissions after-treatment devices [20], as they need specific temperature ranges to operate efficiently [42,45,46]. Among reported investigations on waste energy recovery, it is usual to take hot gases immediately after the turbocharger [10,18], or directly from the exhaust manifold in naturally aspirated diesel engines [15,19,27,41,43]. Studies carried out using spark-ignition engines usually take gases after the catalyst [15–17,33,47].

Energy and exergy characterization of exhaust gases at the outlet of the turbine has resulted in significant differences between energy and exergy values [10]. Measurements from steady state [19,27,43,48] and dynamic [49] operating conditions had been used to characterize energy recovery from exhaust gases by means of heat exchangers, finding recovery potentials up to 15% of fuel's exergy at high engine loads. One reference [50] presents the effect of ambient temperature on exergy efficiency of the engine, finding that this parameter decreases as the temperature increases from −5 °C to 30 °C. Although several researchers have used exergy analysis to study diesel engines, few are focused on energy recovery and none was found to use experimental data from driving conditions. Exergy analysis has proven to be a useful tool to extend the meaningfulness of energy recovery analysis.

In general, it is found that there is a significant fuel saving potential with the different waste energy recovery alternatives, mainly at high engine load and speed. This work focuses on determining the potential for waste energy recovery from the exhaust system of a typical diesel passenger car under the current European driving cycle. Tests were carried out at two different ambient temperatures in a climatic chamber, according to homologation conditions, and two initial engine thermal conditions, cold and