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Modeling Analysis of Waste Heat Recovery via Thermo-Electric Generator and Electric Turbo-Compound for CO_2 Reduction in Automotive SI Engines

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Abstract

In order to face with the increasing EU restrictions on CO2 emissions from light-duty vehicles, concepts such as the engines downsizing, stop/start systems as well as more costly full hybrid solutions and Waste Heat Recovery (WHR) technologies have been proposed in the last years by OEMs. WHR technologies include Thermo-Electric Generator (TEG), Organic Rankine Cycle (ORC) and Electric Turbo-Compound (ETC) that have been practically implemented on few heavy-duty applications but have not been proved yet as effective and affordable solutions for passenger cars. The paper deals with the analysis of opportunities and challenges of TEG and ETC technologies for a compact car, powered by a turbocharged SI engine. Specifically, the benefits achievable by TEG and ETC have been investigated by simulation analyses carried out by a dynamic engine-vehicle model, validated against steady-state and transient experimental data. The in-cylinder processes and friction losses of the engine are modeled by a black-box scalable parametric approach while grey-box dynamic models are applied for intake/exhaust manifolds and turbocharger. The TEG model is based on existing and commercial thermoelectric materials, specifically Bi2Te3. The simulations have been carried out considering standard driving cycles (i.e. NEDC, WLTC) and the results evidence that significant improvement of fuel economy and CO_2 reduction can be achieved by suitable management and configuration of the WHR systems, depending on engine speed and load and auxiliaries demand.

Keywords:.Engine modeling; Powertrain simulation; Waste heat recovery; Turbo-Compound; Thermo-Electric generator.

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Nomenclature

e	Willans conversion efficiency [/]		p_{pump}	Pumping losses [Pa]	
I	Current	[A]	Q	Heat Transfer Rate	[W]
$\dot{m}_{thr}$	Throttle mass flow	[kg/s]	R	Resistance	[Ω]
p_{exh}	Exhaust pressure	[Pa]	T	Temperature	[K]
p_{loss}	Friction losses	[Pa]	T_{exh}	Exhaust temperature	[K]
pma	Mean available pressure	[Pa]	B_c	Compression ratio	[/]
pme	Mean effective pressure	[Pa]	β_{thr}	Throttle Valve position	[/]
P_{MGU}	Electric Motor/Gen Power	[W]	η_{TE}	TEG efficiency	[%]
P_{mod}	Power	[W]	φ_{VVA}	Variable Valve actuator pos. [/]	

1. Introduction

The targets of CO_2 reduction are a big challenge for the transportation sector because the road traffic is the origin of about the 20% of the all CO_2 emissions. The European Commission (EC) aims to reduce the emissions of road transport in 2050 by about 70 % compared with today's levels [1]. In order to reach the 2020 target (average fleet CO_2 emission of 95 g/km), technological evolutions for new vehicles are needed. Despite a specific attention is paid to different powertrain solutions as the electrical vehicles (EV) and hybrid electrical vehicles (HEV), the IC engine will maintain a key role in the next decade to meet the legislation requirements, through the introduction of important improvements. Several studies in the literature, analyse the major developments and the latest advances in terms of potential innovative technologies, and the EC defines guidelines for these 'eco-innovations'[2].In the last years, engines downsizing and stop and start systems have been the dominant trend in engine design for light duty vehicles, but more recently, waste heat recovery (WHR) systems [3][4][5]are one of the major topics of research, as their application may lead to a significant improvement of fuel economy. In fact in current vehicles, a great amount of the fuel chemical energy is wasted through the exhaust gases as heat and expelled to the atmosphere. Part of this heat can be extracted and converted into electricity to re-charge the battery thus reducing the load on the alternator. In the WHR systems, the energy recovery may be achieved by different technologies using, Thermo-Electric Generator (TEG), Organic Rankine Cycle (ORC), Electric Turbo Compound (ETC), etc. This paper focuses on the analysis of the integration of ETC and TEG into a conventional vehicle, specifically aimed at investigating the benefits achievable in terms of fuel economy and CO_2 reduction. The combined application of two different WHR technologies was assessed by Zhang et al. [6], who investigated the idea of combining a TEG with an ORC system for the thermal energy recovery. The ETC was already implemented especially in heavy-duty vehicles[7], nevertheless several studies have been carried out also for both diesel [4]and gasoline-powered passenger cars[8][9]. Moreover, several OEMs and research centers, have demonstrated their interest in the exhaust heat recovery developing systems that make use of TEGs also for light-duty vehicles[5].The results achieved show that the recourse to ETC and TEG devices in passenger cars could lead to an average fuel economy (and CO_2 reduction, consequently) ranging from about 3% to 5% [4][8][9]and 1% to 4% [5], respectively.

2. Modeling Approach

The study presented in this paper refers to a segment C vehicle equipped with a 1.4 liters turbocharged spark ignition (SI) engine with variable valve actuation (VVA). The layout is composed by the standard engine, an MGU mounted on the turbocharger shaft and a TEG system positioned downstream the turbine. A simplified scheme of the ETC-TEG system into vehicle-powertrain layout is shown in Fig. 1a. The electric energy can be generated from two sources: the MGU generates electrical power or drives the compressor, depending on the adopted strategy, and the TEG provides energy to the battery by working on the temperature difference between the exhaust gas and the engine coolant (Seebeck effect) (Fig. 2a). The energy recovered from the exhaust gases can be stored in a battery and/or used to power the auxiliary devices.

The overall model is based on a forward scheme and includes the driveline and the sub-models of the internal combustion engine (ICE), ETC, TEG, alternator and battery. The ICE in-cylinder processes and friction losses are modeled by a black-box parametric approach to ensure scalability; furthermore mean value models are applied for intake/exhaust manifolds dynamics to simulate more realistically the effect of ETC on engine performance. A grey-box approach is considered for the turbocharger and one-state models are applied for the turbocharger shaft dynamics as well as for the vehicle dynamics[8]. The TEG model includes a grey-box sub-model of TE materials (Bi2Te3) and a heat exchanger model for steady-state solutions [5]. The battery is modeled as a first order circuit in the SOC state [10][11] and the alternator is described through an efficiency map function of the engine speed[12]. Arsie et al. [8] give a more accurate description of system actuators control. The engine actuators (i.e. throttle and VVA) are driven in closed loop by PID controllers that operate based on the vehicle speed error, in order to make the vehicle to follow the reference driving transient. The Fig. 1b shows the scheme of the vehicle-powertrain model. The Driver task accounts for the throttle (βthr) and VVA (φVVA) control depending on the vehicle speed error and engine/MGU operation. The benefits achievable by the ETC systems are strongly dependent on the management strategies applied to the MGU. Arsie et al. [8]proposed to set the recovered power proportionally to the turbocharger speed, as far as this latter is greater than a lower threshold to avoid an excessive reduction of the turbo speed. In addition, different control strategies for the alternator management have been developed and the MGU recovered power was limited to 1kW to avoid penalizing the engine performance due to a larger backpressure and, consequently, a lower engine efficiency.

The TEG module model has been identified and validated with respect to existing literature data, showing good agreement with published results. Heat exchanger models for steady-state solutions have been simulated to estimate the actual temperature of hot and cold sides, as a function of vehicle operation and TEG configuration[5].

As aforementioned, this study is aimed at assessing the impact of the combined effect of ETC and TEG; the model provides in output the fuel economy, later converted into CO2 emissions in accordance with the European Commission directive[1], i.e. assuming 2330 g of CO2 per liter of gasoline. Model identification and validation were carried out vs. experimental data collected both in steady-state conditions at the engine test bench and in transient operation on the vehicle test rig[8].Model simulations are performed according to a forward scheme by imposing the vehicle reference speed and gear profiles of any driving cycle. Furthermore, for each simulation analysis, the constraint to recover the initial battery SOC at the end of the driving cycle was imposed.

2.1. Vehicle model

The longitudinal vehicle dynamics is described by means of the driveline sub-model which is based on the Newton law equation [13]. The vehicle dynamics are influenced by longitudinal engine delivered torque, aerodynamic drag forces, rolling resistance forces, slope forces and alternator load (auxiliaries and accessories electrical loads). A parametric approach derived from the Willans line method was applied in order to describe the behaviour of the engine in terms of energy balance [14]. The modelling approach allows evaluating the mean effective pressure by the injected fuel amount, subtracting the losses due to friction, auxiliaries and pumping work:

$$pme = e \cdot pma - p_{loss} - p_{pumping} \tag{1}$$

The parameter is expressed as function of the mean piston speed and mean available pressure (pma). The intake and exhaust manifolds dynamics are simulated through a mean value modelling approach [4][15] and described by means of a set of differential equations in the manifolds pressure and temperature states, based on mass and energy balance. The throttle is modelled as an orifice where the upstream pressure equals the compressor outlet pressure. The air flow to the engine is evaluated through the speed density equation by taking into account the VVA effect on engine breathing [8][16].

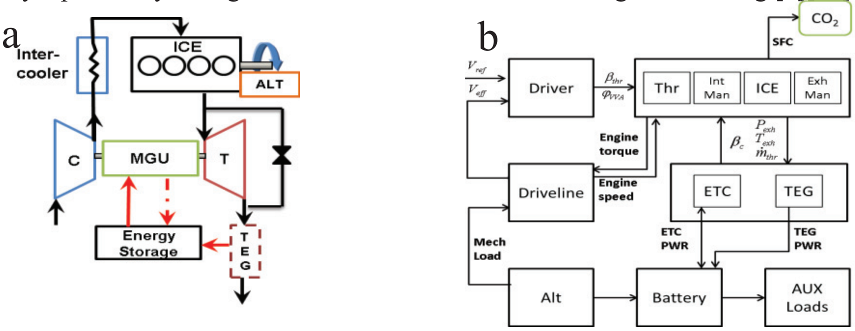

Fig. 1. a) Scheme of the engine equipped with the ETC and TEG systems, including alternator and energy storage devices; b) Scheme of the overall forward vehicle-powertrain model.

2.2. Electric Turbo-Compound model

The ETC system consists of a turbocharger mechanically coupled with a MGU, as shown in Fig. 1a. The MGU can be used either as generator, to recover the exhaust gas energy and power the electric loads, or as motor to move the compressor and boost the engine at low speed, thus reducing the turbo-lag. In this study, the mechanical work recovered by the turbine is converted into electrical energy and then stored in a battery. Thus only the MGU working mode as generator is taken into account. The major recovery from the exhaust gases is obtained by closing the waste-gate (WG) valve. Consequently, the turbine operates on the whole exhaust gas flow and the recovered energy is utilized to power/support the vehicle electrical loads to reduce the alternator resistant torque along the entire cycle. It is worth noting that on one side the MGU allows recovering part of the exhaust gas energy, on the other side it causes larger backpressure with an increase of SFC. The powertrain model allows simulating both these effects, through the mutual interaction between ICE and ETC models, as shown in Fig. 1b and Fig. 2.Compressor and turbine models were identified against mapped data provided by the manufacturer. The compressor model is based on semi-empirical relationships among the flow parameter, the head parameter and the inlet Mach number [17]. These parameters are related to the pressure ratio, the corrected mass flow and the corrected speed through a set of equation defined in Arsie et al. [8]. The turbine is modelled assuming the flow through an orifice both in chocked and unchecked operating conditions. The interaction between turbocharger and MGU is simulated through the power balance equation (i.e. Newton law) applied to the turbocharger shaft.

2.3. Thermo-Electric Generator model

In this study, the model is based on an existing and commercial TE materials (Bi_2Te_3) (HZ-14, produced by Hi-Z Technology, Inc), having ZTs not exceeding 1 and efficiency below 5. Its properties and operating temperature range are suited for the presented application.

The TEG modules are composed by a specified number of thermocouple corresponding to two elements, namely *p* and *n* leg, encapsulated in ceramic boards. The thermocouples are electronically and thermally connected in series and parallel, respectively. The structure of the single TEG couple is shown in Fig. 2b and the corresponding main parameters of a TEG module are mentioned in [5].

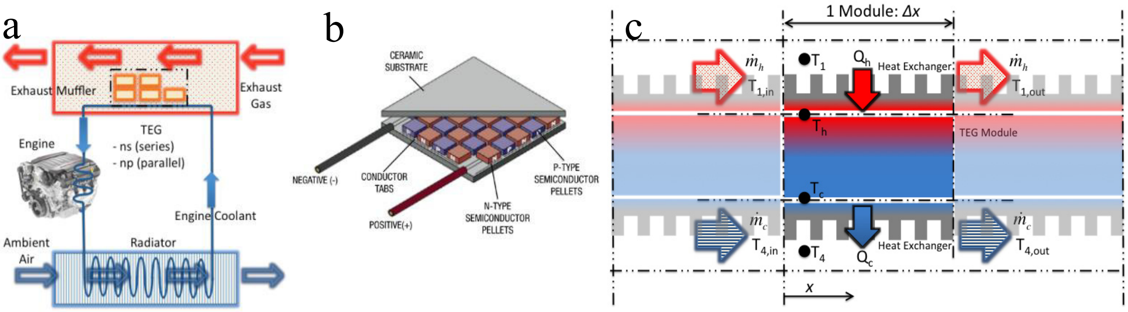

Fig. 2. a) TEG waste heat recovery configuration; b) Thermoelectric module; c) TEG module heat flows.

The specifications are provided by the manufacturer and have not been validated by the authors.

The TEG model is applied at each module connected in series, ensuring the same voltage for all modules[5]. The model inputs are the mass flow rate and temperature of the exhaust gas and incoming coolant. The recovered electric power and efficiency are calculated as:

$$P_{\mathrm{mod}} = I^2 R_{load} \tag{2}$$

$$\eta_{TE} = \frac{P_{\mathrm{mod}}}{Q_h} \tag{3}$$

The power generated by the thermoelectric modules will be used to supply the auxiliaries. For a single module total internal resistance, voltage and current are estimated through the equations described in [5].

The heat flow related to hot and cold side, respectively, is evaluated by the energy balance [5] and correlates the temperatures of the hot and cold side plates of the TEG module to the hot and cold fluid temperatures, see Fig. 2c.When the external load is set to match the TEG module internal resistance, the TEG system produces the maximum output power [5].

3. ETC/TEG control

Despite the fact that the auxiliaries electrical load is not constant along the real driving cycle and exhibits greater values up to 1kW in the initial phase, for the current analysis the power adsorbed by the auxiliaries is assumed constant and equal to 250 W, considering the mean contribution of the typical auxiliaries for a gasoline engine. This electrical load roughly corresponds to the mechanical power requested by the alternator to the engine shaft, thus resulting in an increase of fuel consumption and CO_2 emissions.

The energy recovered by both ETC and TEG devices is stored into the battery pack and then used to power the auxiliary load, thus relaxing the alternator power demand. According to the control strategy considered, the alternator can be electrically disconnected, by cancelling the load on the engine shaft. During the driving cycle, depending on the engine load and the battery state of charge (SOC), different alternator strategies are implemented that envisage the alternator disconnection in urban phase and its application in extra-urban phase. This strategy allows achieving the best fuel economy as the engine operates in the high efficiency working area for a longer time.

Concerning the ETC control, only its operation as generator is considered; the recovered power is imposed to be proportional to the turbocharger speed as far as this latter is greater than a lower threshold, to avoid an excessive reduction of the speed. Furthermore an upper threshold is imposed to the maximum recovered power, set to 1 kW, to avoid an excessive increase of the backpressure with negative impact on engine efficiency.

4. Results

This section presents the main simulation results of the analyzed system in terms of fuel economy and CO_2 reduction, for the driving cycles NEDC and global WLTC. The powertrain model validation vs. experimental data has been presented by the authors in a previous work [8], with a good accuracy of model prediction, especially at high load operating conditions.

The simulation of the baseline system on the NEDC, neglecting the Stop and Start strategy, provides a fuel economy of 16.20 km/l and CO_2 emissions equal to 144 g/km. The Fig. 3 shows the time histories of vehicle speed (3a) and simulated recovered power (3b) for the NEDC and WLTC, by applying the aforementioned alternator control strategy. This latter enables the alternator operation only in the extra-urban phase and has been proved to be the most suited for the energy recovery from the exhaust gases[8].

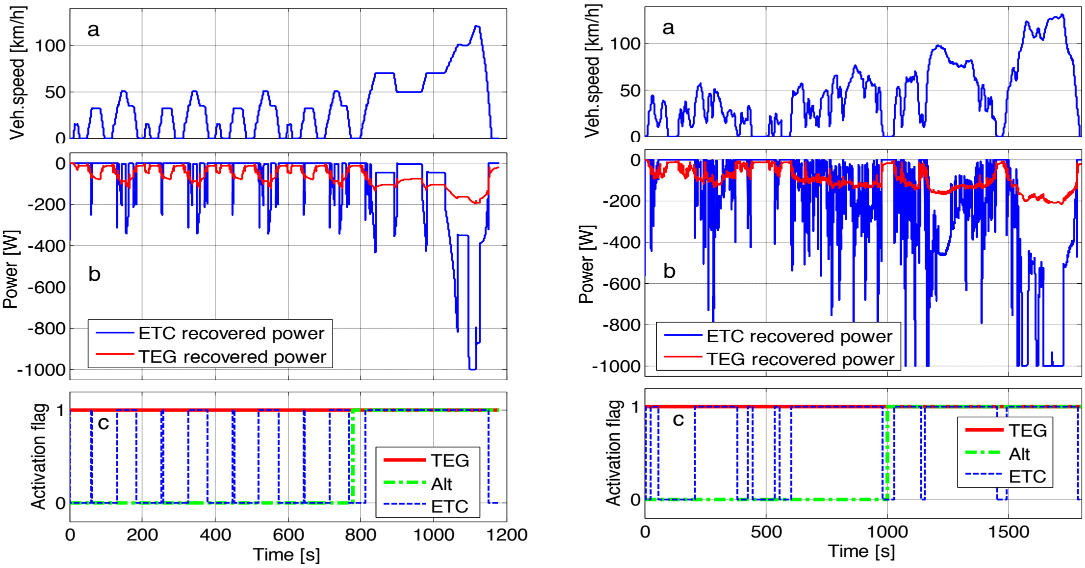

Fig. 3. ETC-TEG analysis on NEDC (left) and WLTC (right): a) measured vehicle speed profile; b) ETC and TEG recovered power; c) actuators activation (1 – on, 0 - off).

The figures evidence that the TEG system exhibits a lower recovered power than the ETC device. On the other hand, the activation flags for TEG, ETC and alternator shown in the lower graphs (3c), evidence that the TEG is always operating whereas the ETC is activated only when the turbo speed exceeds the threshold value of 30000 rpm; consequently, a significant energy recovery from ETC is only achieved at high load operation.

The overall results are summarized in Fig. 4 that shows the reduction of CO_2 emissions achieved with the TEG and the ETC for the two driving cycles considered (i.e. NEDC and WLTC). The blue bars denote the baseline case. Referring to the NEDC, a decrease of CO_2 of about 5% occurs for the vehicle equipped only with the ETC (e.g. red bar), as estimated by Arsie et al.[8]. The TEG implementation in the vehicle model exhibits lower savings, (1.9 % for NEDC, green bar) in terms of fuel economy and CO_2reduction, in agreement with the values presented in the literature [5]. The greatest improvement of fuel economy and CO_2 reduction is achieved by coupling the ETC and TEG. In the NEDC, a reduction of CO_2 emissions down to 5.6 % is achieved. The trend of the simulation results can be easily extended to WLTC as well. In this case a benefit in terms of fuel saving above 6% can be reached, due to the higher engine load conditions.

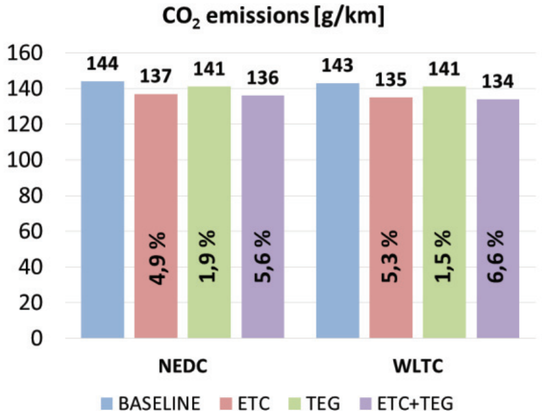

Fig. 4. Estimated CO2 emissions along NEDC and WLTC. The percentages indicate the CO2 savings vs. the baseline configuration.

5. Conclusions

The paper investigates the integration of TEG and ETC systems in a compact car powered by a SI engine. The systems are aimed at recovering the waste energy to improve fuel economy and reduce CO_2 emissions. The simulation analyses have been performed by modeling the TEG and ETC devices into a forward longitudinal model that includes a set of grey-box dynamic models of vehicle, intake/exhaust manifolds, turbocharger and a black-box parametric model for in-cylinder and friction processes.

Several simulations have been carried out to explore different vehicle configurations, considering the standard driving cycles NEDC and WLTC. The results show that the application of both TEG and ETC can lead to a CO_2 reduction ranging from 5.6 % to 6.6 % for the analyzed scenarios.

6. Copyright

Acknowledgements

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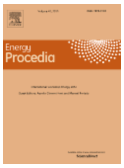

Biography

Ivan Arsie is an Associate Professor in ‘Fluid Machines and Energy Conversion Systems’ at University of Salerno. Degree cum laude in Mechanical Engineering - University of Salerno. PhD in Thermo-Mechanical Systems Engineering- University of Naples "Federico II".

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