Optimization of a Brayton external combustion gas-turbine system for extended range electric vehicles

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Abstract

Significant research efforts are considered in the automotive industry on the use of low-carbon fuels in order to reduce the emissions and improve the fuel economy of vehicles. Some of these fuels, such as the solid fuels for example, are only compatible with external combustion machines. These machines are only suitable for electric powertrains relying on electric propulsion, in particular the extended-range-electric-vehicles with series hybrid configuration where fuel consumption strongly relies on the energy converter efficiency and power density. This paper investigates the fuel savings potential of these vehicles using a Brayton external combustion gas-turbine system as energy converter substitute to the conventional internal combustion engine. An exergo-technological explicit analysis is conducted to identify the best system configuration. A downstream-intercooled reheat external combustion gas-turbine (DIRe-ECGT) system is prioritized, offering the highest efficiency among the investigated systems. An extended-range-electric-vehicle model is developed and energy consumption simulations are performed on the worldwide-harmonized light vehicles test cycle. Fuel consumption simulation results are compared to a reference extended-range-electric-vehicle using an engine auxiliary-power-unit. Results show 6%—11.5% of fuel savings with the prioritized DIRe-ECGT auxiliary-power-unit as compared to the reference model, depending on the battery capacity and the trip distance.

1. Introduction

Automotive manufacturers are investigating the use of alternative fuels in order to comply with GHG and pollutant emissions regulations. Some alternative fuels are compatible with internal combustion engines [1], however others such as solid fuels require the use of external combustion machines, adapted for automotive applications. Many of these machines, namely the external combustion gas turbine (ECGT) [2,3], Rankine machines [4], Stirling engines [5,6], Ericsson engines [7], thermoacoustic [8] and thermoelectric generators [9], have been extensively explored for micro-cogeneration but very few for automotive applications [10,11], and none for the ECGT up to the authors knowledge.

The ECGT, main focus of this study, is based on a gas turbine machine operating according to a modified Brayton thermodynamic cycle, where the air working fluid is heated in a heat exchanger as illustrated in Figs. 1 and 6 (a). This system offers many advantages compared to conventional internal combustion engines (ICE), namely a reduced number of moving parts, vibration-free operation, low maintenance cost, high durability, the absence of water-cooling system [12] and the multi-fuel capability [13]. However, similar to all turbine-based machines, ECGT presents two main drawbacks preventing their use in conventional vehicles: (1) the high fuel consumption and (2) the acceleration lag. These drawbacks are mainly caused by operating the turbine at high speed even in idle conditions, in addition to mechanically coupling the turbine to the vehicle-driving load, which lead to a low efficiency operating range of the system. Moreover, the use of a heat exchanger (HEX) in the ECGT adds a thermal inertia on the upstream of the turbine, which further worsens the acceleration lag, and makes the ECGT system non-compatible for fast response power delivery to follow the variable load applied in conventional powertrains.

Nonetheless, a review of recent research and development programs revealed interests in ECGT for a specific application, where the machine operates steadily at constant speed and drives...
an electric generator. Traverso et al. [14] presented a significant reduction of fuel consumption while operating the ECGT at optimal efficiency point. Roquette et al. [15] showed that the ECGT’s energy efficiency increases with the operating load, and Pierobon et al. [16] showed that the optimal efficiency is not necessarily at full load, and that it is rather reached at partial load.

Therefore, based on the aforementioned findings, ECGT-systems present a forthcoming potential for improving fuel economy and emissions of passenger vehicles, with the benefit of multi-fuel-use flexibility; particularly, in extended range electric vehicles with a series hybrid powertrain configuration (EREV). These powertrains combine a thermal and an electric powertrain in a series energy-flow arrangement [17]. The thermal powertrain in this study is constituted of an ECGT-system and an electric generator, and is referred to as the Auxiliary Power Unit (APU). It operates steadily at the optimum efficiency and mainly used to recharge the battery once depleted. The electric powertrain provides the necessary traction power to overcome the driving load, and it also serves to recover the braking energy. It is important to note that the APU operating speed is cinematically decoupled from the vehicle velocity; therefore, the ECGT operation is controlled to meet its best efficiency. Fig. 2 illustrates the powertrain configuration of the modeled EREV and a simple ECGT-APU system.

On another hand, several ECGT-system options could be considered for integration in EREV, combining a simple ECGT to heat recovery systems and single or multiple-stage compressions and expansions. Few numbers of studies have been published over the past decade in the academic literature treating ECGT-system configurations and performance analysis [19,20,22]. The survey of these studies confirms that most ECGT-systems are designed based on efficiency optimization or on combined cycle overall optimum efficiency when coupled to bottoming cycle [15,23]. However, there are no recent studies on ECGT-systems suitable for automotive applications, due to the lack of competitiveness of ECGT compared to ICE in conventional powertrains. Hence, the following main gaps and limitations in the recent literature are underlined:

- There are no studies assessing ECGT-systems performance based on a Brayton thermodynamic cycle for automotive applications.
- No specific methodology on selecting the best-suited ECGT-system for any type of application is adopted. The studies in the literature focus on the performance investigations of some ECGT-system configurations, without taking into consideration any optimization requirement or technological constraints.
- The overall vehicle consumption under driving conditions is not benchmarked against conventional vehicles and hybrid electric vehicles relying on internal combustion engines.

Therefore, based on the above synthesis of the insights and gaps in the literature for adopting ECGT in automotive applications, this study proposes a comprehensive methodology to identify the potential ECGT-system options and select the optimal system configuration for an EREV application. A methodology for the identification and assessment of the different ECGT-system options applicable to EREV is carried out in section 2, based on exergy analysis and automotive technological constraints. Observed results are then used for the prioritization and the selection of the optimal ECGT-system configuration. The selection criterion is

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**Nomenclature**

AC Alternative Current
APU Auxiliary Power Unit
CC Combustion Chamber
CCB Combustion Chamber Blower
DC Direct Current
DP Dynamic Programming
ECGT External Combustion Gas Turbine
EMS Energy Management Strategy
EREV Extended Range Electric Vehicle
GHG Greenhouse Gas
GT Gas Turbine
HEX Heat Exchanger
ICE Internal Combustion Engine
NSGA Non-dominated Sorting Genetic Algorithm
SOC State Of Charge
WLTC Worldwide-harmonized Light vehicles Test Cycle
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