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Brayton cycles as waste heat recovery systems on series hybrid electric vehicles

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A B S T R A C T

In the global attempt to increase the powertrain overall efficiency of hybrid vehicles while reducing the battery size, engine waste heat recovery (WHR) systems are nowadays promising technologies. This is in particular interesting for series hybrid electric vehicles (SHEV), as the engine operates at a relative high load and under steady conditions. Therefore, the resulting high exhaust gas temperature presents the advantage of increased WHR efficiency. The Brayton cycle offers a relatively reduced weight compared to other WHR systems and presents a low complexity for integration in vehicles since it relies on an open system architecture with air as the working fluid, which consequently avoids the need for a condenser compared to the Rankine cycle. This paper investigates the potential of fuel consumption savings of a SHEV using the Brayton cycle as a WHR system from the internal combustion engine (ICE) exhaust gases. An exergy analysis is conducted on the simple Brayton cycle and several Brayton waste heat recovery (BWHR) systems were identified. A SHEV with ICE-BWHR systems is modeled, where the recovered engine waste heat is converted into electricity using an electric generator and stored in the vehicle battery. The energy consumption simulations is performed on the worldwide-harmonized light-vehicles test cycle (WLTC) while considering the additional weight of the BWHR systems. The intercooled Brayton cycle (IBC) architecture is identified as the most promising for automotive applications as it offers the most convenient compromise between high efficiency and low integration complexity. Results show that 5.5% and 7.0% improved fuel economy on plug-in and self-sustaining SHEV configurations respectively when compared to similar vehicle configurations with ICE auxiliary power units. In addition to the fuel economy improvements, the IBC-WHR system offers other intrinsic advantages such as low noise, low vibration, high durability which makes it a potential heat recovery system for integration in SHEV.

1. Introduction

Engine waste heat recovery (WHR) systems are a promising way to increase the power train efficiency and to reduce vehicle fuel consumption in order to comply with GHG and pollutant emissions regulations. Many of the WHR machines, namely the Brayton machines [1], Rankine machines [2–4], Stirling machines [5,6], thermoacoustic machines [7,8] and thermoelectric generators [9–11], have been extensively explored as WHR systems for automotive applications by most automotive constructers and OEMs [12]. Some of these WHR systems are compatible with low temperature waste heat sources, such as engine coolant. Others are more appropriate for medium and high temperature waste heat sources such engine exhaust gases [13].

The Brayton waste heat recovery (BWHR) system which is a suitable high temperature WHR technology [14], is the main focus of this study. It is based on an open loop turbomachinery system operating according to a modified Brayton thermodynamic cycle, where the working fluid (air) is heated in a heat exchanger as illustrated in Figs. 1 and 7(a). The thermal heat source considered in this study which is the engine exhaust gases, is partially recovered downstream of the catalytic converter through a heat exchanger (HEX) that heats working fluid. The choice of exhaust gases as the hot source offers a high potential of recovered work, since the exhaust gases are at a high temperature when compared to other engine waste heat thermal sources. The turbine provides the mechanical work required to drive the air compressor as well as a generator to produce electricity.

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Nomenclature

E	energy
S	vehicle frontal surface area
Cx	aerodynamic drag coefficient
g	gravitational acceleration
ρ	air density
R	battery internal resistance
M	mass
P	power
R_i	internal resistance
SOC	Battery state of charge
u	Control variable
V	velocity
I	current
V_{oc}	open circuit voltage
η	efficiency
mf	fuel mass

Subscripts

g	generator
m	motor
b	battery
f	fuel
ICE	Internal combustion engine
d	demand

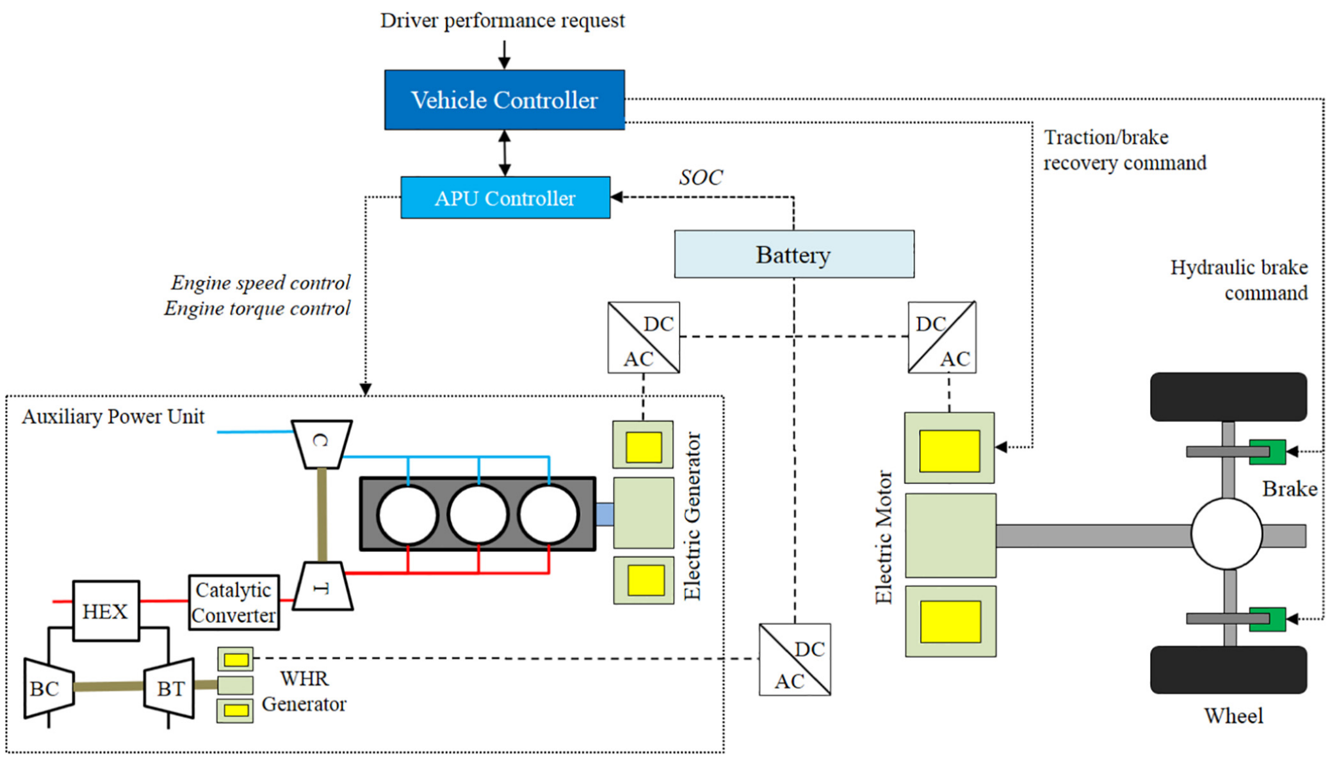

Fig. 1. Configuration of a simple Brayton WHR system on ICE coupled to a series hybrid electric vehicle.

This technology, which is based on the gas turbine system, offers many advantages compared to the other WHR systems, namely a reduced number of moving parts, vibration-free operation and high durability [15]. The high-speed turbomachinery, coupled to the electric generator, offers reduced weight and is congruent with today's vehicle power train components electrification strategy. In addition, BWHR machines present low integration complexity because of the use of ambient air as the working fluid instead of water, ethanol or organic Rankine fluid (ORF) in Rankine systems, or helium, hydrogen and other gases in Stirling and thermoacoustic machines.

However, BWHR systems present low system efficiency in automotive applications which prevents their use as WHR systems in conventional vehicles. This main drawback is caused by:

Low turbine inlet temperature (TIT) due to low exhaust gas temperature during significant portions of engine operation, low net power because of compressor high mechanical work consumption and low amounts of thermal energy power recovered from the exhaust gases, because of the relatively high Brayton compressor outlet temperature.

Moreover, the use of the HEX in the BWHR adds a thermal inertia at the upstream of the turbine, which further worsens the heat recovery during transitory operations and makes the Brayton 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 simple and stationary WHR systems for automotive application, where the machine operates steadily at constant speed and drives an electric generator [16]. For instance, the study of spark ignition engine [17] shows that the constant load conditions in the hybrid vehicle are a potential advantage for the implementation of a heat recovery system. A study at Chalmers University [18] confirms that WHR systems are more favorable in highway driving style where the vehicle runs at constant speed and longer times.

Therefore, based on the aforementioned findings, BWHR systems present a forthcoming potential for improving fuel economy and emissions of passenger vehicles, with the benefit of reliable low complex open loop systems; particularly, in series hybrid electric vehicles (SHEV) which combines a thermal and an electric powertrain in a series energy-flow arrangement [19]. The thermal powertrain consists of an