Energy 86 (2015) 574–588

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance and economic optimization of an organic rankine cycle for a gasoline hybrid pneumatic powertrain

Zlatina Dimitrova*, Pierre Lourdais, François Maréchal

Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 4 February 2015
Received in revised form
11 April 2015
Accepted 15 April 2015
Available online 23 May 2015

Keywords:
Alternative vehicle powertrain hybridization
Hybrid pneumatic powertrain
Organic rankine cycle
Techno-economic evaluation

ABSTRACT

This article presents an innovative concept for alternative hybridization, without electrical devices. The concept is studied on a C-Segment vehicle with targeted prices between 27,000 and 34,000 euros. Short term hybrid pneumatic energy storage and a waste heat recovery system are introduced for the efficiency improvement of a small downsized gasoline engine. The modeling methodology for the hybrid pneumatic powertrain is presented. The waste heat recovery system is an organic rankine cycle. An innovative methodology using energy integration and multi-objective optimization is applied for the design of the organic rankine cycle loop. The selection of the organic rankine cycle design is based on techno-economic indicators and is done by using a qualification utility function for the population of solutions on the Pareto curve. The concept of hybrid pneumatic powertrain and organic rankine cycle is evaluated on different driving cycles and the economic analysis of the customer mobility is done, according to his drive profile.

1. Introduction

1.1. Problem context

With the increasing trend of mobility of the human population, vehicles have to face the problem of primary energy resources scarcity. The vehicles need higher efficiency and better adaptation to the alternative energy sources. Thiel discussed in Ref. [1] the cost and the CO_2 emission regulation in the European Union. The need to improve the efficiency of the vehicle energy system motivates the search for innovative solutions during the design process. Energy breakdown analyses are performed for example in Ref. [2] to improve the vehicle powertrain efficiency.

The main way for vehicle efficiency improvement that the automotive industry takes in the moment is the electrification of the vehicle powertrains. Energy management strategies for hybrid electric vehicles are researched in Ref. [4], and these technologies are improved from cost/effectiveness perspective in Ref. [5]. The hybrid electric vehicles, with different degree of electrification of the powertrain proliferate. The introduction of the electric components in the powertrain leads to increased cost and mass of the vehicles. This is especially due to the relatively low energy density capacity of the high voltage battery. The average storage potential available in serial production is the Li- Ion battery with energy density of 90 Wh/kg or 150 Wh/L [6].

The efficiency/cost balance of the thermal and hybrid electric vehicles is represented on Fig. 1. One can see that there is a technological gap in the zone of high powertrain efficiency (50–80 g CO_2/km) and vehicle cost between 15,000 and 35,000 euros.

This zone in the cost/efficiency balance can be reached with an alternative way of hybridization– the pneumatic hybridization coupled with a waste heat recovery system. This concept uses the combustion engine as pneumatic motor and pump and stores the energy in the tank under pressure. The main mode for propulsion stays still the internal combustion engine. In comparison with the well-known hybrid electric powertrain, the HPP (hybrid pneumatic powertrain) is relatively recent research. Its theoretical basics are presented in Ref. [6] and [7]. There the authors present the basics of the concepts, the modelization approach of the pneumatic modes and also experimental results. The fuel consumption benefit of the pneumatic hybrid system is researched on different driving cycles. The electric components of the hybrid electric powertrain, especially the high voltage battery are expensive and their production and end-of-life phases are not so environmentally friendly. Pneumatic powertrains are gaining interest as an alternative method for

* Corresponding author.
E-mail addresses: pierre.lourdais@epfl.ch (P. Lourdais), francois.machechal@epfl.ch (F. Maréchal).

http://dx.doi.org/10.1016/j.energy.2015.04.047
0360-5442/

Nomenclature

HPE	Hybrid Pneumatic Engine
CV	Charge Valve
HPP	Hybrid Pneumatic Powertrain
ICE	Internal Combustion Engine
NA	Natural Aspirated
NEDC	New European Driving Cycle
HEV	Hybrid Electric Vehicle
ORC	Organic Rankine Cycle
NEDC	New European Drive Cycle
UDC	Urban Driving Cycle
EUDC	Extra Urban Driving Cycle
MGB	Manuel Gear Box
CVT	Continuously Variable Transmission
BMEP	Break Mean Effective Pressure
MILP	Mixed integer linear programming
EGS	Enhanced Geothermal Systems
MOO	Multi Objective Optimization
TES	Thermo-economic Simulation
EI	Energy Integration
TEE	Thermo Economic Evaluation
EMOO	Evolutionary Multi Objective Optimization
MER	Minimum Energy Requirement
CAPEX	Investment cost in Euros
OPEX	Operating cost in Euros
YAC	Yearly annualized cost in Euros

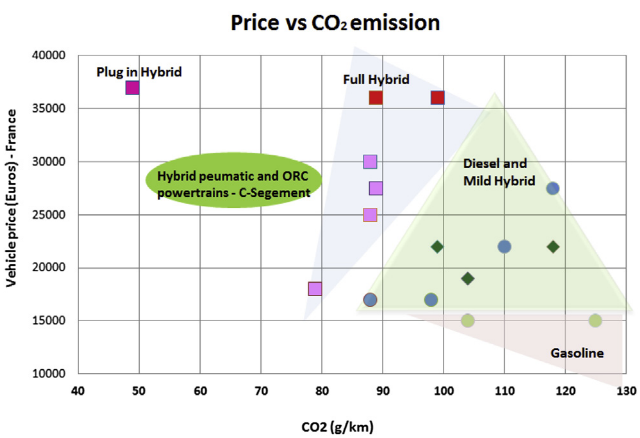

Fig. 1. Price vs CO_2 emission of different hybridizations [3].

powertrain hybridization, as they offer potential alternative in the range of small – middle hybridization, to these drawbacks. The idea in the HPP is to use the engine cylinders and pistons to pump and receive air to and from the air tank. The pistons are recuperating or producing the force, transferred to the engine shaft. The HPP has two different energy sources and can be considered as simplified parallel hybrid, because only the engine shaft provides the link to the drive shaft (Fig. 2). According to Guzzella [6] the energy value of 6.28 kJ/L (1.69 Wh/L) results in the compressed air. The storage in one litter of the Li-Ion battery is 147 times higher than in one litter of compressed air.

In the literature the exploration of the compressed air storage is related to the fuel consumption improvement and the cost reduction for vehicle powertrain applications. Filipi researched the fuel economy improvement of a hybrid pneumatic system in Ref. [8] and Huang et al. in Ref. [9] developed a hybrid pneumatic concept for vehicle powertrain. The article describes the stages of the concept development. All these concepts are developed on four cylinders engines. Also the compressed air is an efficient technology for diesel engines operating strategies and low cost storage tanks, applied in the power generation domain as in Refs. [10,11], where the applications concern diesel engines with large displacement. To sum up the efficiency performances of the HPP are recently researched in the literature but the economic indicators of the concept are not assessed.

An additional fact is that in this kind of alternative powertrains, the internal combustion engine is still wasting a considerable energy under the form of heat. For example Spicher in Ref. [12] determined the energy balance of a thermal powertrain on an analytical way. The results show that 30% of the energy is used for the mobility as mechanical power. The other 70% are wastes – waste heat in coolant ~30% and waste heat in exhaust gases ~40%. Thus this heat can be recovered in mechanical energy and used to increase the ICE efficiency. But once again the energy balance of the losses is used to be done on thermal ICE based powertrains.

Other part of the problem is the sensitivity of the efficiency improvement technologies on the driving conditions. Passenger cars are evaluated in standardized test cycles. In Europe, NEDC is used, and only the energy needed for the propulsion is considered. This cycle is constituted from two parts: UDC – Urban Driving Cycle and EUDC – Extra Urban Driving Cycle (Fig. 3):

Certain robustness of the efficiency gain of the fuel saving technologies on the driving profiles and the comfort demands is then needed. The assessment of the potential of a waste heat recovery system such as an ORC (organic rankine cycle) for integrated

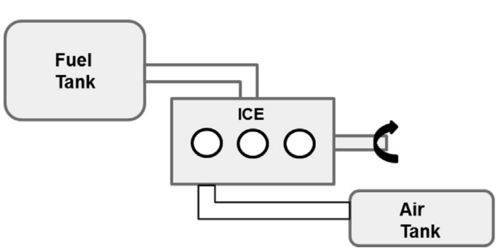

Fig. 2. Pneumatic hybrid powertrain with 3 cylinders engine.

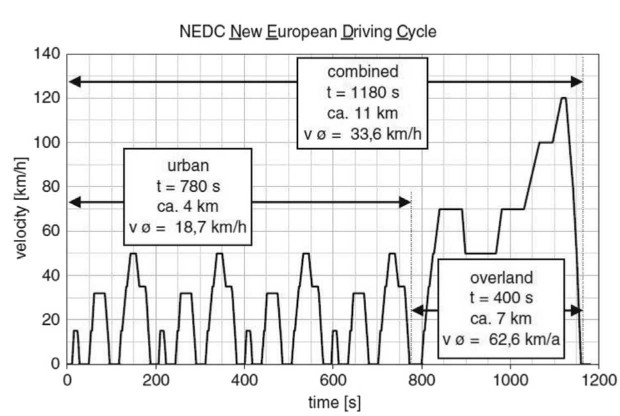

Fig. 3. NEDC characteristics.