Journal of Cleaner Production 67 (2014) 187–196

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Exergoenvironmental analysis of hybrid electric vehicle thermal management systems

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ARTICLE INFO

Article history:
Received 24 December 2012
Received in revised form
17 December 2013
Accepted 17 December 2013
Available online 25 December 2013

Keywords:
Exergy analysis
Exergoenvironmental analysis
Hybrid electric vehicle
Thermal management

ABSTRACT

The exergetic efficiency of the thermal management system (TMS) in hybrid electric vehicles (HEVs) has great importance since the supply of available energy onboard is limited, and that the efficiency is closely tied to the overall environmental impact of the vehicle. Thus, it is imperative to have a good understanding of the thermodynamic irreversibilities and environmental impact associated with the system and its components. In this paper, exergoenvironmental analysis is conducted on hybrid electric vehicle thermal management systems. In the exergy analysis part, the balance equations are written for each system component of the TMS to determine exergy destruction rates and exergy efficiencies of the system and its individual components. In the environmental analysis part, a life cycle assessment (LCA) is carried out (using Eco-indicator 99 points) and environmental impact correlations are created in order to obtain the environmental impact of each relevant system components and input and output streams. Consequently, exergoenvironmental variables are calculated, and exergoenvironmental evaluation is performed to determine the most environmentally friendly system components and provide information about trends and possibilities for design improvements. Based on the analysis, it is found that the electric battery has the highest environmental impact in the system due to the copper used in the anodes and gold used in the integrated circuits which accounts for over 40% and 26% of the overall impact respectively.

1. Introduction

Electric and hybrid electric vehicles are good substitutes for conventional vehicles with internal combustion engines in reducing today's environmental issues such as urban air pollution and global warming (Matheys et al., 2009). They have significant advantages over conventional vehicles with typically higher tank to wheel conversion efficiency and virtually zero tail pipe emissions (Campanari et al., 2009). However, they still impact the environment due to construction, operation, and disposal of their components. Thermal management systems and their components play a significant role in efficiency and environmental impact of hybrid electric vehicles, and therefore it is imperative to analyze their impact under different parameters and operating conditions. Thus, an exergoenvironmental analysis of the TMS is conducted in this study.

The thermodynamic efficiencies of the thermal management systems in EVs and HEVs has great importance due to the limited supply of available energy onboard as well as the overall impact on vehicle performance, and the environmental impact. A detailed understanding of the thermodynamic irreversibilities associated with the system and its components is helpful to improve their energy performance. In this regard, energy-based efficiencies may lead to misleading conclusions, since all energy forms are taken to be equal and the ambient environment is not taken into consideration. The second law of thermodynamics defines the energy conversion limits of the available energy in the system based on irregularities between different forms of energies. The quality of the energy is highly correlated to the reference environment as well as the success level of this conversion capacity, and needs to be considered to prevent achieving incomplete and/or incorrect results. An analysis for examining the work potentials of the initial and final stages of a system can give an evaluation criterion for the quality of the energy. Such analysis is called "exergy analysis", which represents the amount of energy that may be totally converted to work (Arcaklioglu et al., 2005; Ozkaymak et al., 2008).

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http://dx.doi.org/10.1016/j.jclepro.2013.12.041

However, improving the efficiencies of a system may often imply modifications in component design, which a lot of times lead to increasing a parameter (commonly an area, thickness or temperature) that results in an increase in the materials and energy needed for manufacturing the component. This in turn, may increase the consumption of natural resources to produce the component and/or the pollutants generated during its operation. Thus, the system should be evaluated with respect to life-cycle-related environmental impact associated with each component in addition to their thermodynamic efficiencies (Meyer et al., 2009).

In this regard, exergoenvironmental analysis reveals the environmental impact associated with each system component and the real sources of the impact by combining exergy analysis with a comprehensive environmental assessment method, such as life cycle assessment (LCA). An LCA is based on an internationally standardized method that considers the entire useful life cycle of the components or overall systems with respect to their impact to the environment determined by the environmental models (ISO 14040, 2006).

In this study, LCA using Eco-indicator 99 along with impact analyses from the literature are used in order to obtain the environmental impact of each relevant system components and input streams. For the LCA, European electric generation mix and weighting set belonging to the hierarchist perspective (H/H) is used and expressed in terms of Eco-indicator points (Eco-Indicator 99 Manual for designers, 2000) with the help of software package SimaPro 7.2 (SimaPro, 2007).

SimaPro is a life cycle assessment software that has the capability of collecting, analyzing and monitoring the environmental performance of products and services and can model and evaluate complex life cycles in a systematic and transparent way following the ISO 14040 and 14044 series recommendations (ISO 14040, 2006; IS0 14044, 2006). The software is integrated with an ecoinvent database (Ecoinvent, 2012) that is used for a variety of applications including carbon footprint calculations, product design/eco-design as well as assessing the environmental impact with respect to various parameters. The software can define non-linear relationships in the model, conduct analysis of complex waste treatment and recycling scenarios and allocate multiple output processes. Thus, it provides significant value in conducting LCA for the system components (SimaPro, 2007).

During the past several decades, exergoenvironmental analyses have been carried out for various applications by many researchers. Frangopolous and Caralis (1997) developed environomic method which considers the environmental aspects by internalizing external costs caused by pollutants for energy-intensive systems. The authors presented main classes of economic approaches for environmental protection through assessing the unit cost of reducing pollutants by abatement technologies. Moreover, Valero (1995) built on this analysis with exergoecological analysis and extended exergy accounting by introducing additional concepts such as the physico-mathermatical reasoning which underpins the theory of cost allocation through conceptual studies.

Meyer et al. (2009) and Petrakopoulou et al. (2011) conducted exergoenvironmental analysis by taking life cycle of components into account through a cradle to grave environmental impact assessment (using Eco-indicator 99) for energy conversion systems. The authors calculated various exergoenvironmental variables and provided recommendation on the system designs based on these variables. The authors used case studies including a high temperature solid oxide fuel cell integrated with an allothermal biomass gasification process, and combined cycle power olant with chemical looping technologies respectively.

Buchgeister (2010) conducted exergoenvironmental analysis on electricity production using high temperature solid fuel oxide cell (SOFC) with an integrated allothermal biomass gasification process. The authors conducted endpoint life cycle impact assessment method with Eco-indicator 99 and determined that the supply of biomass has the highest environmental impact and that the gasifier, heat exchanger HXA1 and SOFC are the most environment-related components in the system.

Restrepo et al. (2012) presented the results of exergetic and environmental analysis for a pulverized coal power plant by quantifying both the exergy destruction (based on second law of thermodynamics) and environmental impact (based on LCA) associated with the thermal power plant. The authors used SimaPro 7.2 to carry out an LCA and focused on the climate change and acidification impact categories and determined that the largest environmental impact occurred during the combustion process and calculated the CO_2 emissions to be 1300 kg per MWh.

In addition, Tsatsaronis and Morosuk (2008) introduced so called advanced exergoenvironmental analysis (analogous to advanced exergoeconomic analysis) by splitting the exergy destruction and the components' environmental impact into avoidable/unavoidable and endogenous/exogenous parts and demonstrated the concepts through basic case studies. Boyano et al. (2012) applied both conventional and advanced exergoenvironmental analyses on a steam methane reforming reactor for hydrogen production and suggested design improvements based on the environmental impacts associated with the avoidable parts of exergy destruction. The authors determined that the chemical reaction in the combustion chamber is the most significant source of exergy destruction, which can be reduced by reducing the percentage access air and by preheating the reactants. The authors also calculated that the real potential for improving the component-related pollutant formation within the reformer to be only 2% based on the corresponding avoidable environmental impacts for the component.

However, even though several types of exergy based environmental analyses have been used in the literature for various applications, to the authors' knowledge, there have been no models developed to analyze hybrid electric vehicle thermal management systems with respect to LCA based exergoenvironmental analysis. New contributions of this research paper over prior studies can be summarized as follows. An exergoenvironmental analysis is conducted for the first time on hybrid electric vehicle thermal management systems, wherein exergy destruction rates and exergy efficiencies are calculated for the system and its individual components. A life cycle assessment (LCA) is performed and environmental impact correlations are developed in order to obtain the environmental impact of each relevant system components. Also, the exergoenvironmental variables are calculated, and an exergoenvironmental evaluation is performed to determine the environmentally most relevant system components and provide information about trends and possibilities for design improvements.

2. System description

Hybrid electric vehicle thermal management systems (HEV TMSs) are significantly different systems with unique requirements with respect to their commercial and industrial counterparts such as conventional vehicle and residential building air conditioning systems. The TMS needs to handle significant thermal load variations and provide comfort under highly fluctuating conditions, as well as be compact and efficient, and last several years without any significant maintenance. Moreover, the air flow volume, velocity and temperature must be adjustable over a wide range of ambient temperatures and drive cycles without having a significant impact