Energy 65 (2014) 172–181

Contents lists available at ScienceDirect

Energy

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

Whole-vehicle modelling of exhaust energy recovery on a diesel-electric hybrid bus

Ian Briggs*, Geoffrey McCullough, Stephen Spence, Roy Douglas

School of Mechanical & Aerospace Engineering, Queen's University Belfast, BT9 5AH, United Kingdom

A R T I C L E I N F O

Article history:
Received 24 May 2013
Received in revised form
14 August 2013
Accepted 26 November 2013
Available online 22 December 2013

Keywords:
Diesel engine
Turbogenerator
Waste heat recovery
Hybrid
Bus

A B S T R A C T

Hybrid vehicles can use energy storage systems to disconnect the engine from the driving wheels of the vehicle. This enables the engine to be run closer to its optimum operating condition, but fuel energy is still wasted through the exhaust system as heat. The use of a turbogenerator on the exhaust line addresses this problem by capturing some of the otherwise wasted heat and converting it into useful electrical energy.

This paper outlines the work undertaken to model the engine of a diesel-electric hybrid bus, coupled with a hybrid powertrain model which analysed the performance of a hybrid vehicle over a drive-cycle. The distribution of the turbogenerator power was analysed along with the effect on the fuel consumption of the bus. This showed that including the turbogenerator produced a 2.4% reduction in fuel consumption over a typical drive-cycle.

The hybrid bus generator was then optimised to improve the performance of the combined vehicle/engine package and the turbogenerator was then shown to offer a 3.0% reduction in fuel consumption. The financial benefits of using the turbogenerator were also considered in terms of fuel savings for operators. For an average bus, a turbogenerator could reduce fuel costs by around £1200 per year.

1. Introduction

This work studied the effect of waste energy recovery on a 2.4-litre diesel-electric hybrid bus. The aim of the work was to reduce the fuel consumption of the vehicle by using some of the wasted energy on the exhaust line to create useful electrical power for the vehicle. The work was driven by the global need to reduce consumption of fossil fuels as prices and demand continue to rise.

1.1. Automotive industry

Within the automotive sector, emissions of toxic gases such as NO_x (oxides of nitrogen), HC (hydrocarbons), CO (carbon monoxide) and PM (particulate matter) are closely regulated through schemes such as the European Emissions Standard [1]. However, greenhouse gases and fuel consumption are as yet unregulated in the UK, except through tax incentives for end-users who purchase more fuel-efficient vehicles. Within the USA, the CAFE regulations [2] do limit greenhouse gases but only for passenger cars and light trucks. Due to the pressure from market demand, manufacturers and operators are keen to reduce fuel consumption, and hence reduce greenhouse gases, in an attempt to minimise the impact of rising fuel prices.

Due to the inherent inefficiency of the ICE (internal combustion engine), a considerable amount of the fuel energy supplied to the engine is lost as waste heat in both the exhaust line and coolant system. Numerous technologies exist which could be used to recover this lost energy, some of which are described below.

1.1.1. Rankine Cycle

The Rankine Cycle has attracted a considerable amount of interest from automotive manufacturers such as BMW [3], with the turbosteamer concept, which aims to reduce fuel consumption through the use of a Rankine Cycle on the exhaust and coolant loops of the vehicle. Lopes et al. [4] provided an overview of the ORC (Organic Rankine Cycle) systems, and showed the possibilities of using the concept to recover waste heat, and Srinivasan et al. [5] tested an ORC on a diesel engine showing benefits to fuel efficiency and a reduction in emissions. However, whilst these papers prove it is possible to recover significant amounts of waste energy, the complexity of the system, along with the amount of equipment required to make the concept work, is considerable. Due to the size of equipment necessary (including, at minimum, heat exchangers, expander, condenser and pump), the concept may be attractive to

* Corresponding author. Tel.: +44 (0) 28 9097 4569.
E-mail address: i.briggs@qub.ac.uk (I. Briggs).

0360-5442/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2013.11.075

the heavy truck industry, as reported in Nelson [6], which applied Rankine concepts to a 15-litre diesel engine. Although this paper envisioned recovering high amounts of power, the authors also uncovered several obstacles due to equipment size and the amount of pipework required for in-vehicle integration.

Domingues et al. [7] showed the potential of an ORC to recover waste heat from a 2.8-litre gasoline engine. The authors showed up to 3.5% using an optimised heat exchanger. The authors recognised the complexities of the system, which included low efficiency (the maximum reported system efficiency was 18%) and high operating pressure of the working fluid (up to 40 bar for maximum efficiency).

1.1.2. Thermoelectric power

A number of studies have also investigated the suitability of TEGs (thermoelectric generators) to recover waste heat. These devices use a temperature gradient to create electricity based on the Seebeck effect. Crane [8] suggested TEGs could be applied to a purpose-built radiator to recover heat from the coolant line. Modelling results show up to 2 kW of energy could be recovered, but this required the engine to be operated aggressively, and is not necessarily representative of real-world driving conditions. Such a device is expensive, and the efficiency of the TEGs suffer from heat transfer effects on the vehicle's exhaust line.

Rowe [9] highlighted how existing materials are limited in their maximum operating temperature, which limits the automotive applications. Fairbanks [10] also showed how TEGs are better suited to low-power situations such as personal heating or cooling applications. Gou et al. [11] studied the potential for thermoelectric generators to recover waste heat from a radiator. A comprehensive modelling study showed that a TEG (thermoelectric generator) could recover a maximum power of 6 W with a working temperature of just 90 °C. As this was applied to the coolant loop of a vehicle, the maximum temperature was therefore limited to this low value, which in turn limited the power produced from the device. The efficiency of the overall TEG system was also very low; generally the efficiency was below 0.5% in all simulations.

However, all these papers agreed that the power density of the commercially-viable TEGs is currently too low to have a serious benefit in the automotive environment. The maximum efficiency of the materials in these devices is approximately 5%, so further developments in thermoelectric material technology are required before they can recover a suitable amount of energy from the main sources of heat on the vehicle.

1.1.3. Turbomachinery

Turbocharging is intended to increase the volumetric efficiency of the engine. By charging the air on the intake stroke to higher than atmospheric pressure, an increased mass of air is drawn into the cylinder, which facilitates the injection of more fuel, thereby increasing power density. The turbocharger makes use of the exhaust gas which would otherwise be wasted at the end of the exhaust stroke of the piston, due to the geometrically given expansion ratio [12].

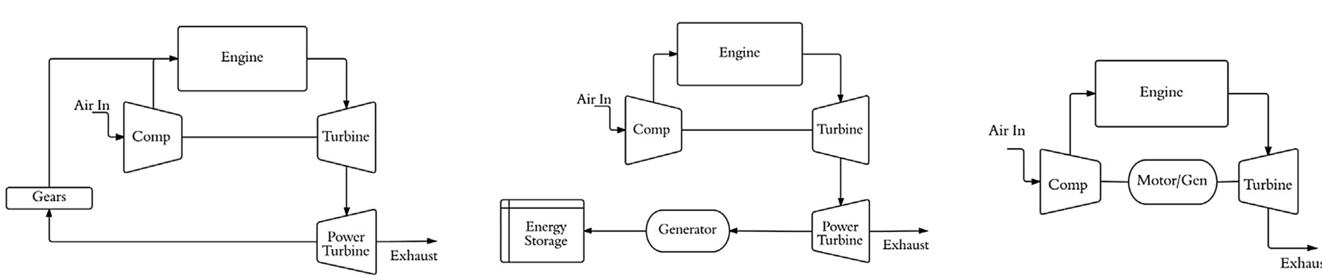
Turbocharging, in conjunction with engine downsizing, can also be used to provide the same amount of power from a smaller capacity engine, and due to the reduction in capacity, less fuel is required. Hence, turbocharging can be used to reduce fuel consumption.

The principle of turbocompounding extends this theory and places a second 'power' turbine on the exhaust line, usually downstream of the turbocharger turbine, linked to either a set of gears connected to the crankshaft (mechanical turbocompounding) or a small electric generator (turbogenerator). Alternatively, the turbocompound can take the form of a motor/generator on the shaft of the turbocharger (electric turbocharger). The three forms of turbocompounding are shown in Fig. 1.

Turbocompounding, in its various forms, has been shown to offer significant benefits in fuel consumption for large capacity engines. Sendyka and Soczówka [13] showed a 5–10% improvement in fuel consumption using a modelling approach applied to an electric turbocharger. This study also showed the best results were obtained when the engine was run at high load. Hopmann and Algrain [14] also showed the benefits of turbocompounding at full-load on a large-capacity engine. They reported up to 10% reduction in fuel consumption through a theoretical modelling approach, and up to 5% reduction in fuel consumption when real-world engine loads were analysed. Hountalas et al. [15] compared mechanical turbocompounding to an electric turbocharger. The authors showed the mechanical setup to be the best configuration, delivering up to 4.5% reduction in fuel consumption at full-load on a large-capacity engine. The electric turbocharger produced almost no benefit at part-loads, but the authors showed the importance of matching the turbocharger to the new turbocompounded setup; if a revised turbocharger was used with increased efficiency, almost 3% reduction in fuel consumption was achieved.

1.1.4. Turbogenerator

Of the forms of turbocompounding discussed, the turbogenerator offers benefits to fuel consumption, high power density and small packaging requirements. Thompson et al. [16] studied a turbogenerator on a 12-litre engine. The turbogenerator was run at a fixed speed and load point, but the authors showed that the power turbine speed was a key parameter to obtain maximum benefit from the turbogenerator and when the turbogenerator design was optimised, 9.1% improvement in fuel consumption compared to the baseline turbocharged engine was achieved. This highlights an additional benefit which the turbogenerator offers over mechanical



(a) Mechanical Turbocompounding (b) Turbogenerator (c) Electric Turbocharger

Fig. 1. Turbocompounding layouts.