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Characterisation of a low pressure turbine for turbocompounding applications in a heavily downsized mild-hybrid gasoline engine

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A B S T R A C T

This paper describes the outcomes of a study carried out on a novel exhaust energy recovery system for a heavily downsized gasoline engine. The investigation was carried out based on a 1.0 L turbocharged gasoline engine offering the same performance as a 2.0 L model, with the aim of reducing CO_2 emissions from 169 g/km to 99 g/km. This is to be obtained by the synergistic application of electrified boosting, stop/start technology, regenerative braking, torque assist and exhaust energy recovery systems.

The research focussed on the design of a high performance LPT (Low Pressure Turbine) to recover latent energy left in the exhaust gas after expanding in the main turbocharger turbine. The LPT is meant to be coupled to an electric generator whose combination is usually referred as *electric turbocompounding*. Given the small engine size and therefore the low mass flow rate of the exhaust gas, the design operating conditions were fixed at 50,000 rpm with an optimum pressure ratio of PR $\approx$ 1.1. Commercially available turbines are not suitable for this purpose due to the very low efficiencies (less than 40%) experienced when operating in such low pressure ratios range. The design was accomplished by following a number of steps which go from meanline loss model development, full 3-D CFD (Computational Fluid Dynamics) analysis (using ANSYS CFX), prototype manufacturing and steady-state testing. The test results, that were conducted by using the Imperial College London cold-flow test facility, showed good agreement with CFD analysis with an efficiency greater than 70%.

The steady maps obtained from testing were then input into a 1-D engine model including the electric turbocompounding. Three different arrangements were considered for the turbocompounding: (1) pre-catalyst, (2) post-catalyst and (3) in the wastegate of the main turbocharger. Two different scenarios were investigated in which the extra energy recovered by the turbocompounding unit is either fully regenerated into the engine crankshaft or stored and not re-used. The BSFC (brake specific fuel consumption) and the BMEP (brake mean effective pressure) were calculated and compared with the baseline engine under full and part load conditions. At full load, the analysis was performed for several engine speeds (from 1000 rpm to 6000 rpm at steps of 500 rpm each). The results showed that the extra energy recovered by the turbocompounding device is offering a significant benefit on engine performance; the post-catalyst solution offers the best compromise in terms of BSFC and BMEP with an improvement of 2.41% and 2.21% respectively. At part load engine instead, the analysis was performed for three engine speeds (1500 rpm, 2000 rpm and 4000 rpm) for the post-catalyst position only. Despite the increment in pumping work due to the presence of the LPT, no significant penalty in BSFC was calculated when no energy is returned into the engine whereas an improvement of $\approx$2.64% was found in the other case.

1. Background and objectives

Cumulative greenhouse gas emissions between now and 2050 will strongly impact the extent of the climate change by the end of this century. According to estimates of 2007, global transport sector alone accounts for around 23% of all energy related CO_2 emissions and this percentage is likely to increase as other sectors are decarbonised [1]. The pace for carbon dioxide reduction is set by legislation or binding agreements coming into force in the most industrialised countries. Fig. 1 shows a comparison of the historical fleet performance and the stringency of forthcoming regulations

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Nomenclature

BMEP	brake mean effective pressure [bar]
BSFC	brake specific fuel consumption [kg/kW × hr]
C	absolute flow velocity [m/s]
d	diameter [m]
FFR	fuel flow rate [kg/hr]
ICE	internal combustion engine
LPT	low pressure turbine
k	specific heat ratio
$\dot{m}$	mass flow rate [kg/s]
MFP	mass flow parameter $[(kg/s)/(K^{0.5}/Pa)]$
ORC	Organic Rankine Cycle
P	pressure [Pa, bar]
PLR	part load ratio
PR	pressure ratio
R	gas constant [kJ/kg × K]
T	temperature [K]
U	rotor velocity [m/s]
VR	velocity ratio
W	power
Δ	difference [kW]
γ	cone angle
η	efficiency

Subscript

0	total/stagnation condition
1	volute inlet
2	stator inlet
3	rotor inlet
4	rotor exit
bl	blade
is	isentropic
t-s	total-to-static

for global light duty vehicles to 2025. It is apparent that, although most countries set their future targets of CO_2 reduction to an average rate of 3–4% a year, future legislation in the major markets (like EU and US) demands that this pace of change must be doubled.

So far, four main challenges need to be tackled in order to reduce carbon emissions for ICEs (Internal Combustion Engines). These can be listed as follows: (i) enforce strict emissions legislation and control, (ii) use sustainable new fuels, (iii) reduce fuel consumption and (iv) enhance energy saving concepts [2]. Consequently more and more legislators started to apply stringent emission regulations by introducing vehicle taxation schemes and green zone areas in order to limit CO_2 levels in urban areas. However, despite providing an immediate benefit in terms of air quality, such restrictive solutions need to be supported by an adequate improvement in powertrain systems. It is within this context that automotive manufacturers are currently looking into novel technologies capable to provide reliable and cost-effective solutions to maximise exhaust energy recovery and hence mitigate CO_2 emissions. Hybrid and full electric vehicles represent the future in the transportation sector, however a full switch over is still long to come and this is one of the main reasons pushing automotive industry to invest more and more resources into exhaust energy recovery systems.

Despite the improvement in efficiency of ICEs, 25%–35% of the overall energy available to the engine is wasted through the exhaust gas. Therefore, it is apparent that there is great scope for all those technologies enabling to recover the excess energy from the exhaust gas and to regenerate it either into the engine crankshaft or into auxiliary powertrain units within the vehicle. The combination of exhaust energy recovery systems with readily available solutions for downsized engines like direct injection engine, stop/start technology and regenerative braking can achieve up to 40% CO_2 emissions reduction [4].

As part of the HyBoost project, the current study focuses in the design and the development of a high performance LPT for electric turbocompounding. The HyBoost project is a TSB[1] research programme which aims to produce a car running on a 1.0 L turbocharged gasoline engine offering the same performance as a 2.0 L engine while reducing CO_2 emissions from 169 g/km to 99 g/km. This has to be achieved by the *synergistic application of engine downsizing, electrified boosting, mild-hybrid functionalities with stop/start and regenerative braking, novel energy storage technology, torque assist and electric turbocompounding*. The main outcomes of this research are given in the following discussion.

2. Research activity in exhaust energy recovery systems

At the present, three main technologies are being studied for exhaust energy recovery in the automotive sector: ORCs (Organic Rankine Cycles), thermoelectric generators and electric turbocompounding. The key features of each of these technologies are given in Table 1 which also shows the engineering layout associated with each one of them. As one can imagine each technique embeds positive and negative aspects which make it hard to establish a clear winner. However in the following discussion we will try to highlight the *pros* and *cons* of each of these technologies with particular focus on turbocompounding.

The study of ORCs application to recover some energy from ICEs has being studied by several researchers since 1978 [5–7]. Organic Rankine Cycles offer waste heat recovery without imposing any additional back-pressure to the engine as it does not restrict the exhaust gas flow leaving the engine. In ORCs the exhaust heat is recovered by an evaporator which is located after the main turbocharger (e.g. direct evaporation embedded in the exhaust pipe). As the evaporator is exposed to high exhaust gas temperatures, the ORC fluid changes phase from a highly compressed liquid to a superheated vapour which is then expanded in a turbine generating electric energy. Despite a potential improvement in BSFC (Brake Specific Fuel Consumption) of as much as 15%, the implementation of ORCs requires a complex engineering architecture which makes it not a favourable solution for small scale applications [5] (such as passenger vehicles). In addition to this, low cycle efficiency (less than 40%) coupled with high implementation costs makes it simpler and more efficient devices to be preferred to ORCs.

Similarly to ORCs, thermoelectric generators do not increase exhaust back-pressure. The principle behind thermoelectric generation relies on the Peltier–Seebeck effect which accounts for the conversion of thermal energy of the exhaust gas into electric energy. The electric current is produced by a temperature difference between the cold and hot surfaces of the thermoelectric generator exchanging heat with the wall of the exhaust pipe; this causes the charge carriers in the thermoelectric surface to diffuse thus producing thermally induced current. The implementation of thermoelectric technology in ICEs is expected to reduce fuel consumption

[1] The Technology Strategy Board is an executive non-departmental public body established by the UK Government and sponsored by the Department for Business, Innovation and Skills.