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Waste heat recovery using a novel high performance low pressure turbine for electric turbocompounding in downsized gasoline engines: Experimental and computational analysis

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ABSTRACT

The development of a high performance LPT (Low Pressure Turbine) for turbocompounding applications in downsized gasoline engine is presented in this paper. The LPT was designed to fill the existing technology gap where no commercially available turbines can operate effectively at low-pressure ratios (1.05–1.3) to drive an electric generator with 1.0 kW power output. The newly designed LPT geometry was tested at Imperial College under steady-state conditions; a maximum total-to-static efficiency, η_{t-s} 75.8% at pressure ratio, $PR \approx 1.08$ was found.

The LPT performance maps were then used for a validated 1-D engine model in order to assess the effect of turbocompounding on BSFC (Brake Specific Fuel Consumption). Then a prototype of the LPT was tested in the post catalyst position on a 1.0 L gasoline engine for different operating conditions. The test results showed that reduction in BSFC of 2.6% could be achieved.

With the post-catalyst position selected, a KP (key-point) engine speed/load analysis was performed in order to project an overall NEDC (New European Drive Cycle) fuel consumption benefit for the LPT in a mechanical turbocompounding configuration, as well as an overall power benefit calculation. Finally, a sensitivity study indicated what the power could be off-cycle.

1. Introduction

In 2010, global transport sector consumed approximately 14.65 trillion kWh of primary energy including hydrocarbon fuels. The cumulative energy consumption for transportation sector from 2010 to 2035 is expected to increase by 0.2% per year and subsequently in 2035 the total energy consumed will approximately be 15.2 trillion kWh [1]. Despite the higher demand for energy, the amount of primary energy resource is declining and the fossil fuel reserve is depleting at faster pace than in the past. Thus, the effect of fuel volatility is significant in heat engine energy conversion. Essentially, the energy conversion technique must be improved for long-term sustainability [2]. This can be achieved by improving energy conversion technology as well as energy recovery systems.

The concept of energy recovery is not novel. However, there is great scope for all those technologies enabling energy recovery out of the exhaust gases, cooling water and unburned fuel. Some of the energy recovery systems are described in detail below.

1.1. Exhaust waste heat energy

It is anticipated that the cumulative GHG (greenhouse gas) emissions between now and 2050 will strongly impact the extent of climate change by the end of this century. According to Energy Outlook Report in 2010 the global transport sector solely accounts for around 23% of all energy related to CO_2 emissions and this is likely to increase as other sectors are decarbonised [3]. The pace for carbon dioxide reduction is set by legislation or binding agreements that have been coming into effect in most industrialized countries. Fig. 1 shows a comparison between historical fleet

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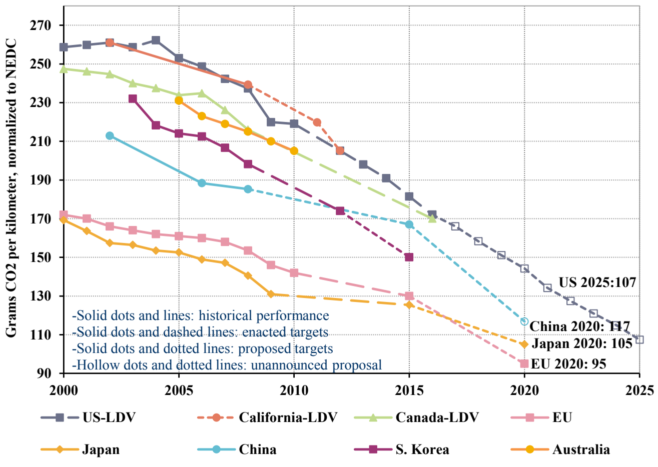

-Solid dots and lines: historical performance
-Solid dots and dashed lines: enacted targets
-Solid dots and dotted lines: proposed targets
-Hollow dots and dotted lines: unannounced proposal

[1] China's target reflects gasoline fleet scenario. If including other fuel types, the target would be lower
[2] US and Canada light-duty vehicles include light-commercial vehicles

Fig. 1. Historical fleet CO_2 emissions performance and current or proposed standards [5].

performance and the stringency of forthcoming regulations for global light duty vehicles up to 2025. Although most countries set their future targets for 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 rate to be doubled.

Taylor et al. [2] proposed four strategies that can be adopted in decarbonizing emissions from ICE (internal combustion engines). The strategies include: (i) enforcing strict emissions legislation and control, (ii) using sustainable fuels, (iii) reducing fuel consumption and (iv) using enhanced energy saving concepts [2]. Currently, many legislators have started to implement stringent emission regulations by introducing vehicle taxation schemes and green zone areas in order to control carbon emission levels in urban areas. Despite providing an immediate benefit in terms of air quality, such restrictive solutions need to be supported with a long-term plan to improve powertrain systems and therefore reduce carbon emission. It is due to this context that the automotive manufacturers are prompted to look into novel technological capability in providing reliable and cost-effective solutions to maximize energy recovery as well as to mitigate carbon emissions. Hybrid and full electric vehicles represent a viable solution in the transportation sector, however a switch over from ICEs to full electric vehicles has long way to come. Thus investment into exhaust energy recovery is a sensible short term to medium term solution.

1.2. Exhaust energy recovery for internal combustion engine

Current techniques to recover exhaust gas energy in the automotive sector can be divided into, (1) ORC (Organic Rankine Cycle), (2) Thermoelectric Generation and (3) Turbocompounding. Each technique has its own advantages and disadvantages. Therefore, it is difficult to establish a clear winner among them. However, in the following discussion we will try to highlight the merits and deficits of each technology mentioned above focussing mainly on the turbocompounding system. Fig. 2 shows the architecture/working principle of ORCs.

Many researchers have actively investigated Organic Rankine Cycles for waste heat recovery in ICEs since 1978 [4–15]. The working principle is similar to the thermodynamic cycle vapour power plants. In automotive applications, the exhaust gases leaving the engine provide thermal energy which is needed to trigger the ORCs. An evaporator (i.e. heat exchanger) filled with organic fluid - such as Freon R11 (CCl_3F), R114 ($C_2Cl_2F_4$), Toluene ($C_6H_5CH_3$), Benzene (C_6H_6), or Fluorinil (FC_3CH_2OH) – is located downstream of the engine exhaust. As the heat exchanger is exposed to the high exhaust gas temperatures, the organic fluid flows into the heat exchanger (in liquid state) will then leave as superheated vapour. The high-pressure superheated vapour expands in the turbine to generate electrical power, via a coupled generator.

In static gas turbine applications, Larjola [6] used Toluene as working fluid to implement an ORC system due to its good thermal stability and being less harmful to the environment than conventional fluids. Larjola [6] found that as much as 26 kW can be recovered from a 1500 kW gas turbine electric generator. The integration of ORCs as part of a vehicle powertrain increases the thermal efficiency of the engine without significantly increasing the exhaust back-pressure. The reason being is that ORCs do not obstruct the flow thus minimizing the impact on pumping losses. A maximum power output of 2 kW has been shown so far in passenger cars [7–9]. However, despite a potential improvement in *BSFC* (Brake Specific Fuel Consumption) of as much as 15%, the implementation of ORCs requires a complex technological

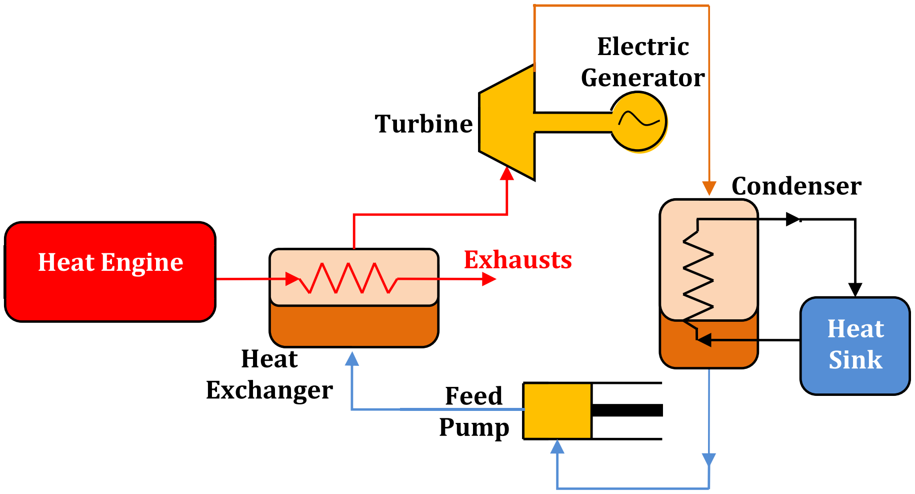

Fig. 2. ORC schematic layout.