Imperial College London

EXHAUST GAS ENERGY RECOVERY IN FUTURE ENGINE TECHNOLOGIES

Research areas within the Imperial College turbochargers group - www3.imperial.ac.uk/turbochargers

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Unique turbochargers test facility

Energy recovery is a key goal for fuel efficient internal combustion engines. Imperial has a unique turbine test facility capable of steady and unsteady operation. For this purpose, the group has developed a state-of-the-art eddy current dynamometer (Fig. 1) with has a much wider test range than traditional gas test stands. The dynamometer works on the principle of eddy current braking by incorporating 14 magnets onto a rotor. The rotor spins co-axially to a set of stationary water-cooled conducting plates known as stators, which are located, either side of the rotor (Fig. 2).

The turbine maps that can be obtained cover a range which is around four times the width of standard maps (velocity ratio ranging from 0.3 to 1.1 -Fig. 3-, pressure ratio going from 1.0 to 3.0 -Fig. 4- and power capability ranges from 60kW to 500W).

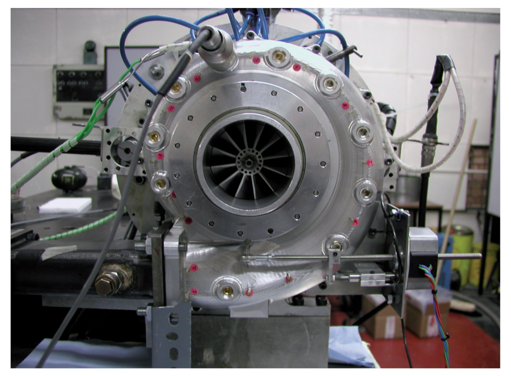


Fig. 1: Eddy current dynamometer

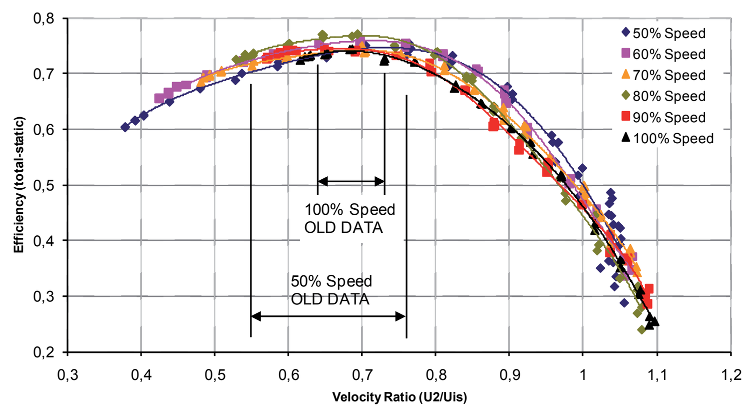


Fig. 3: Turbine performance map, Efficiency vs. velocity ratio

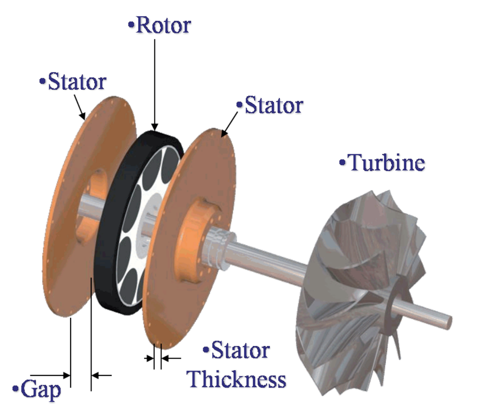


Fig. 2: Rotor, stator plates

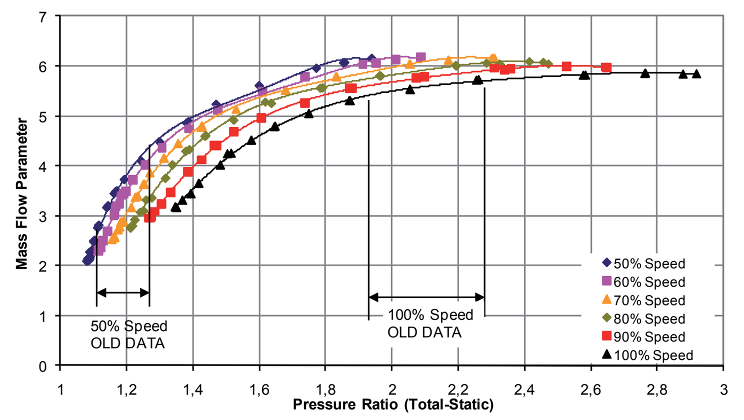


Fig. 4: Turbine performance map, Mass flow vs. pressure ratio

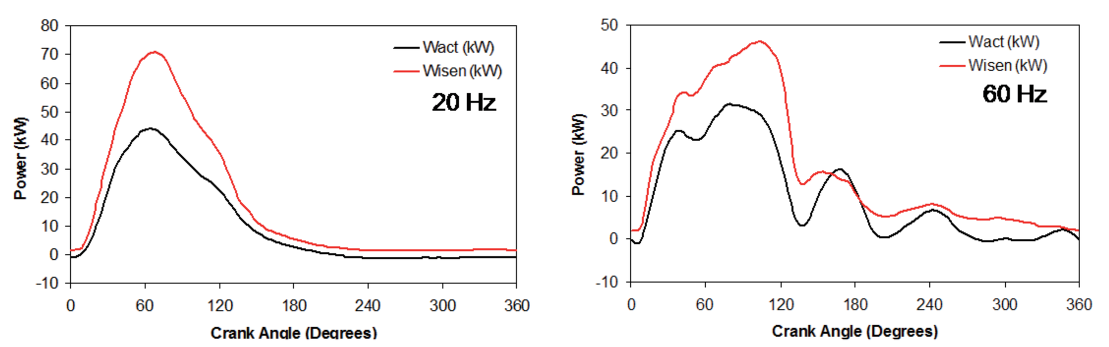


Fig. 1:Instantaneous power

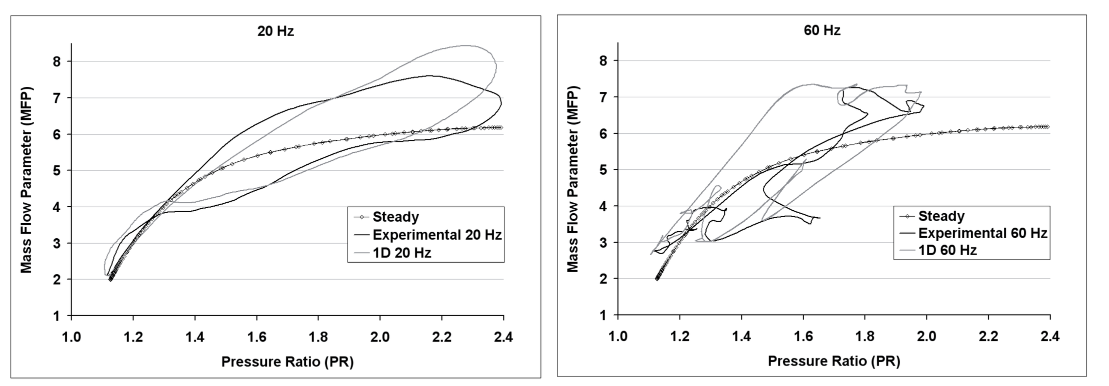


Fig. 2:Hysteresis-type turbine characteristic

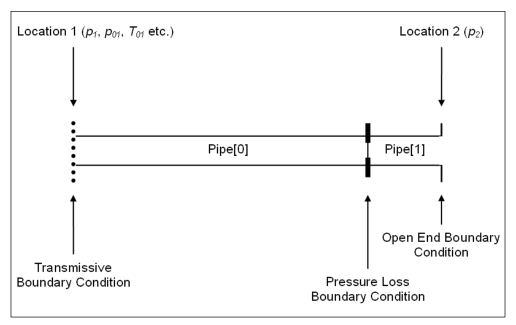


Fig. 3: ONDAS configuration

Unsteady Analysis (ONDAS)

The turbine stage of a turbocharger is subjected to an unsteady flow field due to the rapid opening and closing of the reciprocating engine exhaust valves. Despite substantial research efforts over the past decades, the knowledge of the flow field and performance in a turbocharger under pulsating conditions is rudimentary. Consequently, the mechanisms that cause a hysteresis-type turbine characteristic (Fig. 2) are investigated within the group. In order to achieve this goal, the turbocharger facility measures all the instantaneous relevant quantities: mass flow rate, rotor speed, temperature, pressure and torque. Hence, the instantaneous power available as well as the actual developed power is obtained (Fig. 1). This investigation opens the way to understand when optimum energy conversion takes place.

A one-dimensional wave action code (ONDAS) -Fig. 3- for turbines has been developed and it aims at improving the selection and prediction performance the complex pulsating conditions. The method is sufficiently low order, while representative, to be incorporated in engine design methods. Figure 2 shows the prediction of mass flow of a single entry turbine leading to a good degree of accuracy for different frequencies.

Racing green

Some 800 million passenger cars and light trucks are operated today . If current trends continue, this number is likely to double by 2040. As a result, exhaust gases emitted to the atmosphere and the demand for petrol inevitably will increase. Low Carbon Vehicles (LCVs) are means of transport with a substantially lower carbon footprint than the average current vehicle fleet. These include highly efficient cars with internal combustion engines (ICEs), Hybrid Electric Vehicles (HEVs), Plug-in-Hybrid Electric Vehicles (PHEVs), Fuel Cell Vehicles (FCVs), Electric Vehicles (EVs).

The research at Imperial College's Energy Group for Sustainable Futures focuses on the readiness of current low carbon vehicles and the potential impact that LCVs can have in the future. In the UK for instance, there are currently just over 33,000 hybrid electric vehicles and pure electric vehicles. This equates to a mere fraction 0.1%! Both, experimental tests and theoretical simulations (Fig. 1) have shown that hybrid electric vehicles can achieve more than 40% better fuel economy compared with conventional cars.

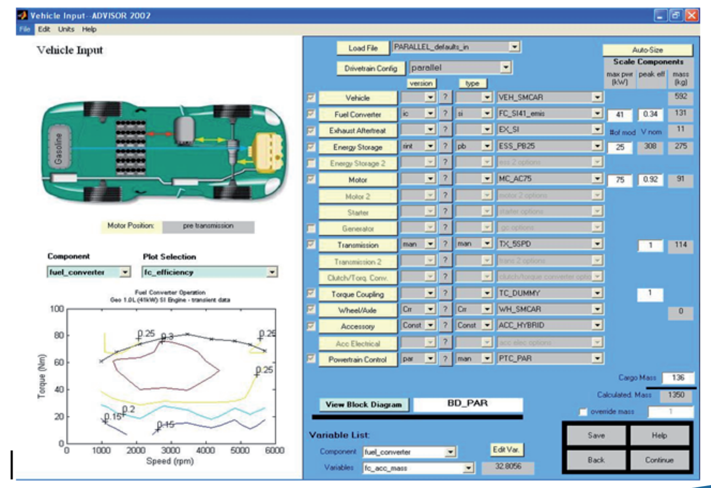


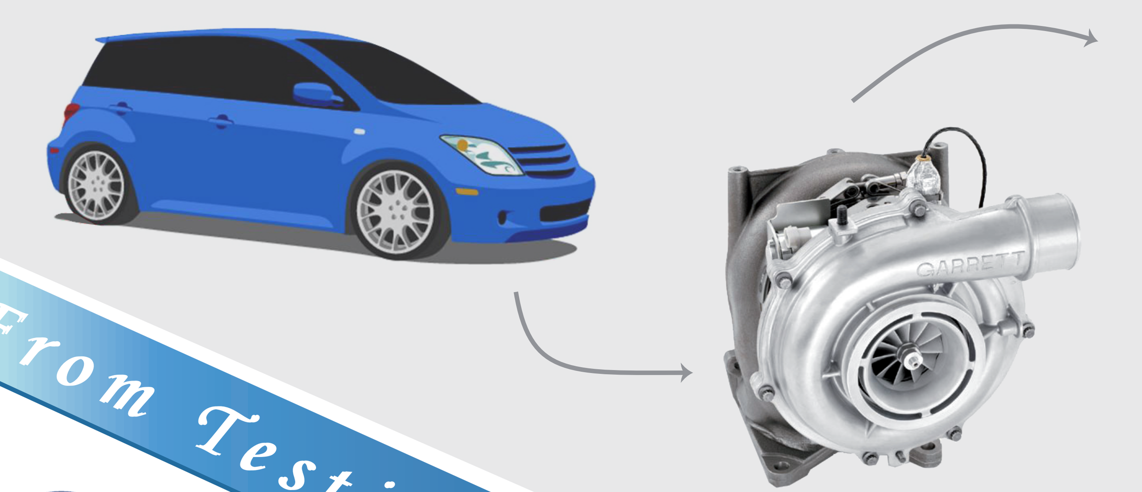
Fig. 1: Simulation for hybrid electric vehicle

How fast can a battery-powered car travel the entire 16,000+ mile length of the Pan-American highway? We don't really know but it looks like we're going to find out. The Racing Green Endurance team, hailing from Imperial College London, are putting together an all-electric version of the Radical SR8 (now an SR0) to demonstrate to the world the possibilities of this powertrain.

racing green ENDURANCE

IMPERIAL COLLEGE TURBOCHARGERS GROUP:

Imperial's position at the cutting edge of new technology research is reflected in the expertise and development of the turbocharger testing facility. Advanced and novel technologies for energy efficient engines being developed at Imperial include active flow control and electric turbo-assisted technologies. The team also has expertise in electrification and downsizing of turbochargers, increasing the engine efficiency to reduce the size. Knowledge of various software modelling packages, including Star-CD, CFX, Ricardo WAVE and a bespoke in-house code for gas dynamics calculations (ONDAS), gives the group the advantageof combining experiments and computations.



Main research activities:

- *Experimental investigation*
- *Unsteady analysis (ONDAS)*
- *Computational fluid dynamics(CFD)*
- *Active Control Turbocharger (ACT)*

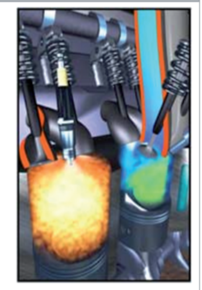
Complimentary projects:

- *HyBoost*
- *Racing green endurance*

From Testing to Design through Computational analysis

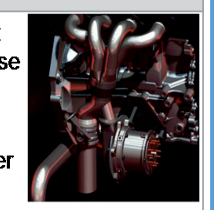
Downsized Gasoline Engine

- Downsized, highly boosted gasoline engine gives improved fuel economy at low cost
- Downsizing results in operation at high load factor and generates high exhaust enthalpy



E-Charger and Electric Turbocompound

- E-charger for improved transient response and potential to increase pressure ratio
- High speed switched reluctance machine attached to turbocharger shaft
  - Acts as generator, turning exhaust enthalpy into electricity



Low Cost Energy Storage

- 12V AGM Lead Acid battery plus supercapacitors
- Allows high current operation for engine stop/start and turboshaft acceleration
- Supports micro-hybrid operating modes
- Compatible with existing 12V vehicle architecture

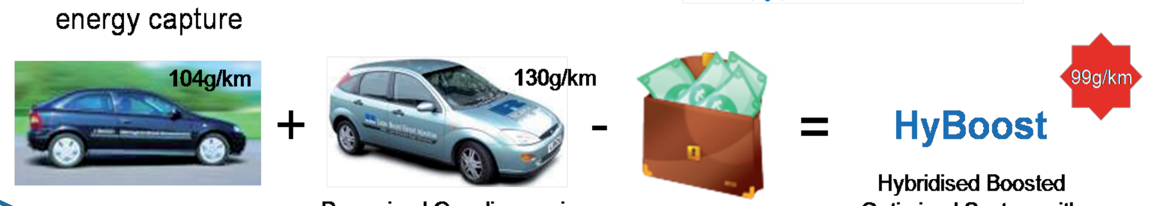
Micro-Hybrid

- 12V or 12+X belt mounted electric machine allows:
  - Engine stop/start operation
  - Mild regenerative braking
  - Efficient electrical generation
  - Delivery of turbocompound electricity to crankshaft
- Mounted in position of conventional alternator

- **12+X systems**
  - Belt-ISG
  - Electric supercharger
  - Lead Acid (12v) + Supercap ("+X")
  - Optional electric turbocompound
- **Engine re-optimisation**
  - Downsizing through uprating
  - Turbo optimised for steady state efficiency
  - Partial Miller cycle for maximised energy capture

"HyBoost aims to demonstrate the very significant benefits that can be achieved using an intelligent combination of innovative technologies to deliver low carbon transport solutions. The stated targets of this research would enable a consumer-attractive "average car" to be offered with CO2 emissions well below the mandated future target set for the European fleet average without compromising vehicle performance"

HyBoost



Downsized Gasoline engine with re-optimised cycle

Hybridised Boosted Optimised System with Turbocompound

HyBoost is a research collaboration of Ricardo, CPT, Valeo, Ford, Imperial College and Ealabac, funded by the UK Technology Strategy Board

HYBOOST

Imperial College's Group for Sustainable Energy is involved in the HyBoost project that is a research programme which aims to demonstrate a very cost-effective,ultra-efficient gasoline engine in a C-segment passenger car. The vehicle will offer the performance of a 2.0 litre model but with a real-world 30-40 per cent reduction in CO2 emissions to below 100g/km. This is to be achieved through the synergistic application of an extremely downsized gasoline engine coupled with electrified boosting and exhaust gas energy recovery, micro-hybrid functionality with stop/start, torque assist and regenerative braking, and a novel energy storage technology (refer to figures on the left handside)

The technologies to be incorporated in the HyBoost demonstrator vehicle will be restricted to innovations which are capable of practical production implementation in the near term; they must be constructed with readily available and affordable materials, and have the high scalability required by the automotive sector.

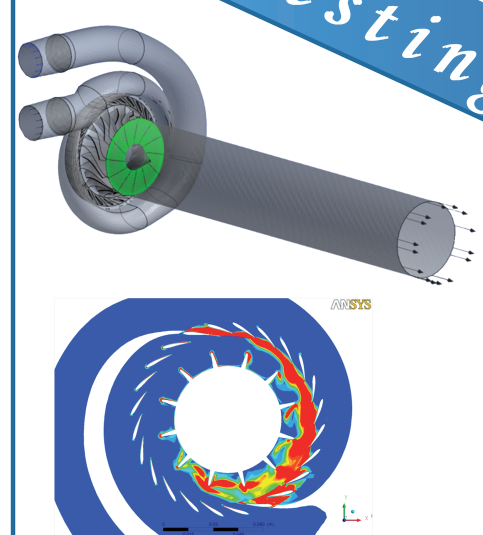


Fig. 2: CFD analysis

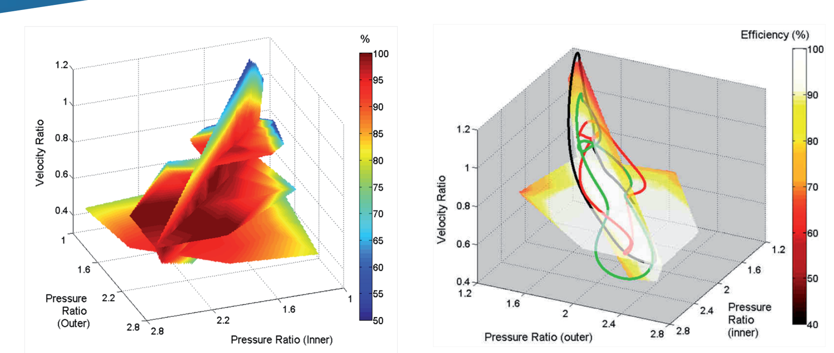


Fig. 1: Dual entry turbine 3-D map

Computational Fluid Dynamics (CFD)

The ability to test dual entry turbines and vary the flow rate in each limb independently coupled with the ability of the dynamometer to allow testing to a far broader range of conditions than possible with an aerodynamic loading device means that it is possible to build up a much more complete picture of turbine performance than is possible on many other turbine test facilities. Figure 1 shows a 3-D map for a double entry turbine, the vertical surface shows the turbine performance under equal admission conditions, the horizontal surfaces show the turbine performance under unequal admission conditions at three different values of velocity ratio.

Computational Fluid Dynamics (CFD) is used as a tool to compliment the extensive experimental work carried out on the test facility (Fig. 2). The vast amount of data collected from the test facility can be used to validate the CFD model which can then be used as a further insight into the flow field within the turbine. The figure shows contours of entropy generation rate in a double entry turbine under partial admission conditions. Here there is a large amount of entropy generated in the mixing layer where the flow from the active limb meets the stagnant air in the non flowing limb.

Imperial Innovations

CARBON TRUST Making business sense of climate change

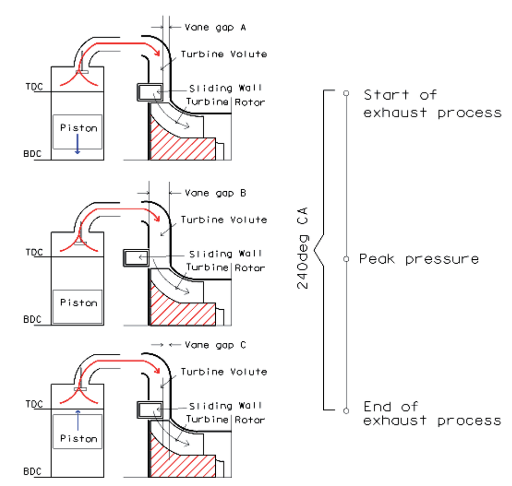


Fig. 1: ACT technology

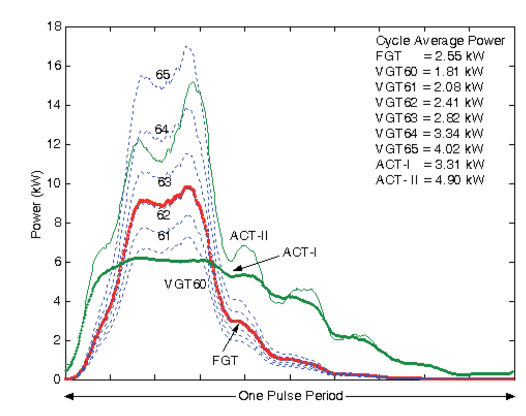


Fig. 2: ACT energy recovered (green line)

HOW DOES IT WORK?

ACT technology provides suitable inlet area to the turbine throughout each engine exhaust gas pulse period (Fig.1) in order to:

-take advantage of exhaust pulse energy levels

-match turbine geometry more efficiently to the engine exhaust flow characteristics

BENEFITS OVER VGT (Variable Geometry turbine)

- *Up to 7% exhaust energy recovered by turbine (Fig.2)*
- *5% increase in engine brake power*
- *0.5% increase in thermal efficiency*
- *Projected power improvements in new versions of the ACT to exceed 20% brake power*
- *Potential for engine downsizing by 20% in terms of combustion chamber volumetric capacity*

Active Control Turbocharger (ACT)

<u>Technology</u> The device is a means to improve the turbo-charging of internal combustion engines, in particular diesel engines. Additional energy is extracted from the engine exhaust by an innovative technique that considers the fluctuations in exhaust pressure over small time periods. The innovation increases the available power from the turbocharged engine by up to 20%. In addition, the use of the ACT turbocharger control produces a gain in thermal efficiency of the engine in the order of 2%, as more energy is extracted from the engine exhaust, which in turn increases the useable energy which can be obtained from a given mass of fuel.

<u>Markets</u> These turbocharger improvements will benefit all applications of turbocharged internal combustion engines, this effect is especially valuable to stationary power and other applications where operation is fairly constant and running costs are key business drivers. Imperial is looking to license this technology to leading turbocharger manufacturers.

<u>Management</u> The development of the technology is currently being supported by Imperial Innovations and the Imperial Carbon Trust Incubator. A business development manager has been engaged to attract and negotiate with potential licensees for the technology.

ImperialCollege turbochargers group constantly collaborates with the world's leading car and turbocharger manufacturers:

Visit our website: *www3.imperial.ac.uk/turbochargers*

ABB · BorgWarner · CATERPILLAR · CPT · EPSRC Pioneering research and skills · EVO ELECTRIC the evolution of power · Ford · Honda · Institution of MECHANICAL ENGINEERS · MITSUBISHI MOTORS · RICARDO · Technology Strategy Board Driving Innovation