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TURBO-COOLING APPLIED TO LIGHT DUTY VEHICLE ENGINES

Whelan, Chris & Richards, Roger, WDL ltd, UK

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ABSTRACT

The concept of charge air-cooling by turbo-expansion applied to internal combustion engines was developed in the 1950s. It was successfully applied to natural gas fuelled power generation engines, enabling useful power increases & providing protection from detonation effects caused by varying gas properties.

On light duty engines for passenger cars & light trucks, the application of turbo-cooling offers a range of thermodynamic opportunities. Any turbocharged engine can be turbo-cooled, although the potential benefits vary with both the combustion type & the application. The key principle is to achieve increased intake charge pressure combined with reduced charge air temperature. This can offer benefits in respect of detonation, thermal loading, with control over combustion rates & in-cylinder pressures.

On gasoline engines there is an increasing use of turbocharging, which opens up opportunities for turbo-cooling to enable improvements in performance, fuel economy & emissions. The majority of light-duty diesel engines are turbocharged. Their maximum power potential is dictated by a combination of boost system & structural limits that can potentially be extended by turbo-cooling.

This paper presents a study into the application of turbo-cooling to light duty engines. The basic concept & historical work are presented. 1-D performance simulation & simple thermodynamic analyses are used to present a scenario for a gasoline light duty engine system. The potential for improvement in power output, fuel economy & emissions are explored, both qualitatively & quantitatively.

Concept designs & potential production applications of turbo-cooling are also reviewed, together with a roadmap for development & market introduction.

BACKGROUND

The concept of charge air-cooling by turbo-expansion applied to internal combustion engines was developed in the 1950s & 60s *[1,2]*. It was successfully applied to natural gas fuelled power generation engines, enabling useful power increases & providing protection from detonation effects caused by varying gas properties.

Little or no work in this field appears to have been performed during the 20-year period after these studies & applications. In the mid-1980s the author carried out experimental work *[3]* as part of a Formula 1 racing engine programme. The regulations then allowed unlimited boosting of a gasoline 1.5 litre 4-stroke engine. A detonation-limited combustion system, in combination with significant excess exhaust energy, encouraged investigation of the turbo-expansion concept. Rig tests were performed to establish feasibility, & engine designs prepared. The system was never vehicle tested.

In the early 1990s a theoretical study *[4]* was made into the use of charge refrigeration for emissions improvements on medium & heavy-duty diesel & gasoline vehicle engines. The study concluded that the application was feasible, & the effects of various component efficiencies were explored.

Again little further work was performed until 2003, when results of a modelling & design study, based on a mechanically driven positive displacement system, were published *[5]*. Experimental testing on a 2-litre gasoline engine, was published in 2005 *[6]*, but proved disappointing.

In 2003, the authors considered that current regulatory, technical & market trends in light duty powertrain development warranted a further study into turbo-cooling systems.

OPERATING PRINCIPLES

The operating principle of turbo-expansion is well known; the flow path & main components are shown in Fig.1. The sequence of 'events' for the charge air is:

- Compression by the compressor of the main turbocharger (Turbo1)
- Cooling by the first charge air cooler (CAC1)
- Further compression in the compressor of the turbo-expander (Turbo2)
- Cooling by the second charge air cooler (CAC2)
- Expansion through the turbine of the turbo-expander (Turbo2)

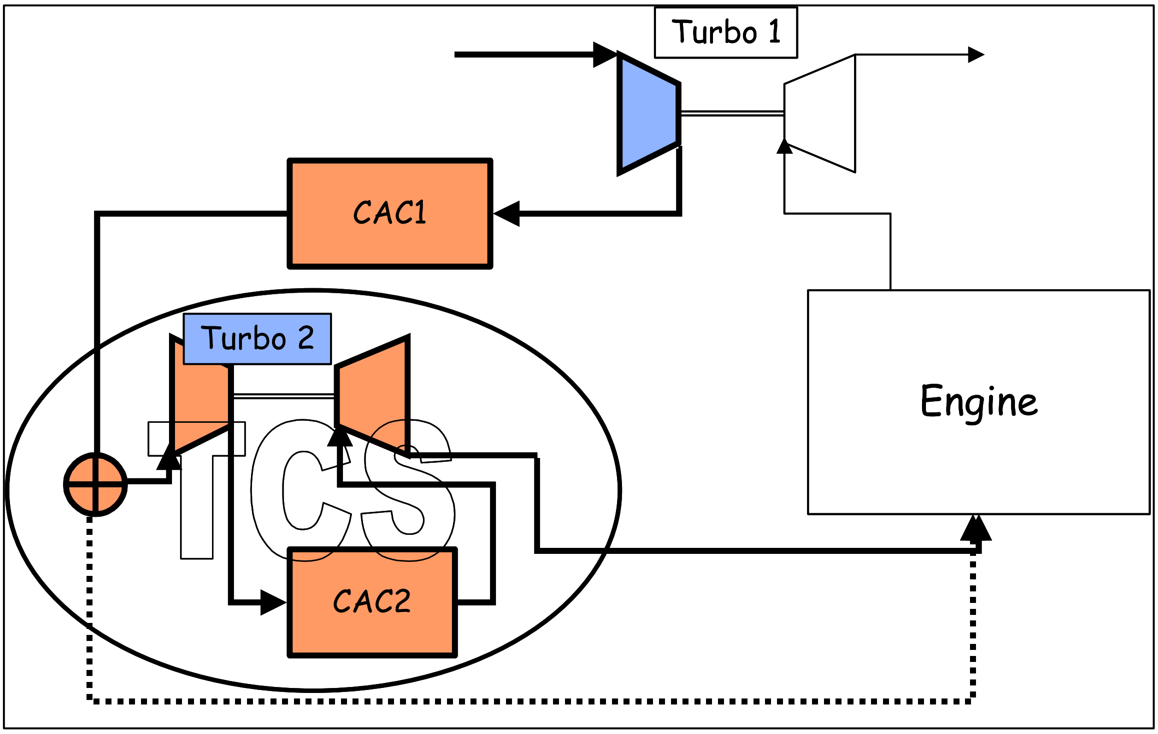

Fig.1: Turbo-Cooling System (TCS) Layout & Gas Flowpath

Air expansion through the turbo-expander turbine provides the power to drive its compressor. The overall loss of enthalpy through this second stage of compression & expansion is compensated for by increased work in the first compressor. The net effect on the engine is increased exhaust manifold pressure into the main turbine.

In summary, for a given charge air volume flowrate & density, which generally defines the indicated engine power, the intake pressure & temperature can be lowered at the expense of high primary boost pressure & increased engine pressure gradient (& pumping loss). The benefits of turbo-expansion result from the various ways of exploiting reduced intake pressure & temperature.

Before considering a modern application of turbo-cooling, it is important to understand the current technical & market trends that would support its introduction onto road vehicles.

CURRENT TRENDS & OPPORTUNITIES

On engines for passenger cars & light trucks, turbo-cooling offers a range of thermodynamic opportunities. Any turbocharged engine can be turbo-cooled, although the range of potential benefits varies with both the combustion type & the vehicle application. The key principle is to achieve increased intake charge density combined with reduced charge air temperature. This can offer benefits relating to power output, detonation, thermal loading & engine-out emissions, linked with additional control over combustion rates & in-cylinder pressures.

Some specific recent technical trends are worthy of review in the context of turbo-cooling.

Downsizing

For passenger cars, drive-cycle based fuel economy can be improved by reducing engine capacity for a given power & vehicle weight. The drive-cycle power demand is fixed, so with a smaller capacity engine the load (Pme) increases, resulting in improved specific fuel consumption. These gains are not always realised in real-world driving conditions. European vehicle manufacturers are aggressively pursuing engine downsizing, in support of the ACEA CO_2 target reductions for 2008 & 2012.

There are penalties resulting from engine downsizing that differ between gasoline & diesel engines.

On diesel engines, higher engine loads significantly increase engine-out NOx emissions. There is also some deterioration in low speed performance ‘feel’ due to the transition from near normally-aspirated torque to very high levels when the boosting system becomes effective. A potential solution to this problem is the application of electrically driven boost ‘augmenters’ (e-boosters). A combined e-booster & turbo-expander is reviewed later.

On gasoline engines, the low speed torque transition problem is similar to that of diesels, but less severe. Additionally there are fuel economy issues resulting from ‘real-world’ driving. This is due to enriched air-fuel mixture at high engine loads, necessary to control thermal loads, exhaust temperatures & combustion stability within acceptable levels. With downsized engines it is possible to regularly cruise the vehicle in the enriched operating zone of the engine, with a resulting deterioration in fuel consumption & range. There are also emissions issues, due to the deviation from a stoichiometric air-fuel ratio, leading to imbalance in the 3-way catalyst.

The study will indicate how turbo-cooling can alleviate these penalties.

Specific Power

Whilst technically closely linked to downsizing, continuing increases in specific power also result from other influences. For example, the selling price of a passenger car is correlates more with the power output of the engine than with its capacity. This results in a wide range of power ratings for given engine sizes, & the need to increase the power for a given package size as well as displacement. It is much easier to develop a medium sized car with a medium sized engine of high power than it is to install a bigger displacement engine.

These trends apply both to gasoline & diesel engines & are driving up the specific power of all engine sizes. Increases in power are subject to well-known constraints. For both engine types, intake pressure & temperature are key influences on maximum power. For gasoline engines, this is due to effects on combustion stability, thermal efficiency & thermal loading. On diesel engines they relate to the mass & durability of the engine, via mechanical loading (max. cylinder pressure) & thermal loads (high-cycle fatigue).

Emissions & EGR

Although emissions influences run through the subjects presented above, it is worth considering the special needs of medium & heavy-duty diesel engines. These engines must conform to emissions limits over a wide range of engine speeds & loads, often resulting in the need to operate with exhaust gas recirculation (EGR) at high engine loads. This can lead to two very specific problems. On these engines the pressure gradient across the engine is broadly positive, as opposed to highly negative on small engines, resulting in the need for special devices to induce an EGR flow from exhaust to intake. Also, significant EGR cooling is required to contain the intake charge temperature to acceptable levels. This is compounded by the need to increase charge air boost pressures to compensate for the air displaced by the EGR; a vicious circle. Turbo-cooling potentially offers relief both in terms of engine pressure gradient & intake temperature.

High load EGR has also been considered for highly boosted gasoline engines, as a means of controlling combustion stability without fuel enrichment. This approach brings similar problems of controlling intake manifold temperature. The current approach is EGR cooling with engine coolant, which is in-efficient, package demanding & increases the size & mass of the vehicle cooling system. These effects are counter-intuitive to the concept of light, efficient downsized engines & vehicles.

Turbo-cooling potentially addresses these issues, in terms of engine pressure gradient, intake temperature & EGR conditions.

Future Combustion Systems

This paper does not aim to review the vast body of work performed on pre-mixed auto-ignition combustion systems (HCCI & CAI). In the context of turbo-cooling, the critical issue is intake temperature control. For combustion stability in HCCI/CAI mode, & the transitions to/from ‘normal’ combustion operation at medium/high loads, accurate & precise control of intake charge temperature is a ‘must’. Turbo-cooling can play a significant & useful role of the future application of these combustion systems.

CASE STUDY

As discussed above, there is a range of potential applications of turbo-cooling to vehicle engines. This paper will present just one these; namely the downsized gasoline engine. However, this simple study will clearly indicate some elements of turbo-cooling that may be applied to other engine & vehicle types.

Approach

The downsizing study approach is based on the following scenario:

- A turbocharged 1.6 litre engine replaces a normally-aspirated 2.0 litre passenger car engine; an exercise performed by numerous manufacturers & investigators. The power is typically 110kW
- Power of the 1.6 litre engine is increased to the practical limit of the base design, to provide a high performance vehicle & wider product range. The maximum power is typically 150kW.

The second step above is the key element of this study. The effect of increasing the power of the simple turbocharged engine is compared with a similar power increase using turbo-cooling.

Modelling Technique

The case study presented below has been performed using AMESim 1-D modelling software. This time-based multi-physics software package includes all the elements necessary for thermodynamic simulation of the complete turbo-cooling powertrain, including:

- Gas flow path (properties & geometry)
- Turbo-machinery (scalable maps & non-dimensional parameters)
- Heat exchangers (maps or heat transfer functions)
- Engine model (mean-value or fully-defined)
- Control loops & functions
- Vehicle definition & mission profile operation, as required

The circuit models developed for the standard (Baseline) engine & the turbo-cooling (TCS) versions are shown in Figs. 2 & 3. The TCS device modelled is a typical turbocharger. Production TCS systems would also feature a bypass loop for engine operation without turbo-cooling; this has been omitted in this study to simply the modelling. The red lines & icons relate to control functions. These include functions for CAC performance matching & turbine area control according to various charge air inputs. A typical strategy is to modulate the main turbine area so as to maintain constant intake pressure or temperature. This study uses the 'mean value' engine model, with fixed efficiency & heat rejection, but with varying pumping loss. This approach reduces complexity in order to concentrate on TCS operation. For specific applications the available full 'emptying & filling' engine model would be used.

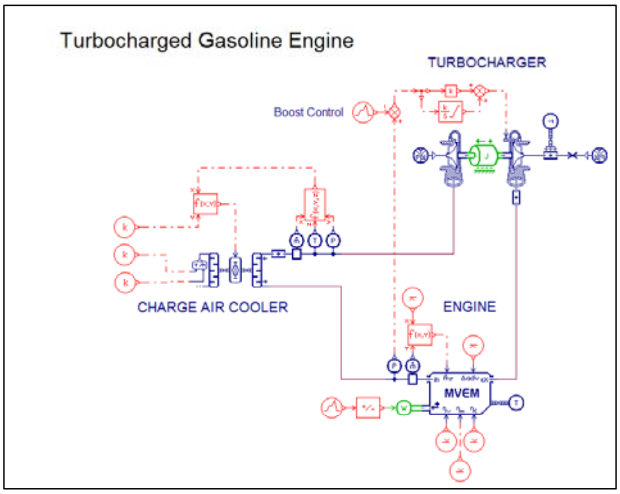

Fig.2: AMESim model: Baseline

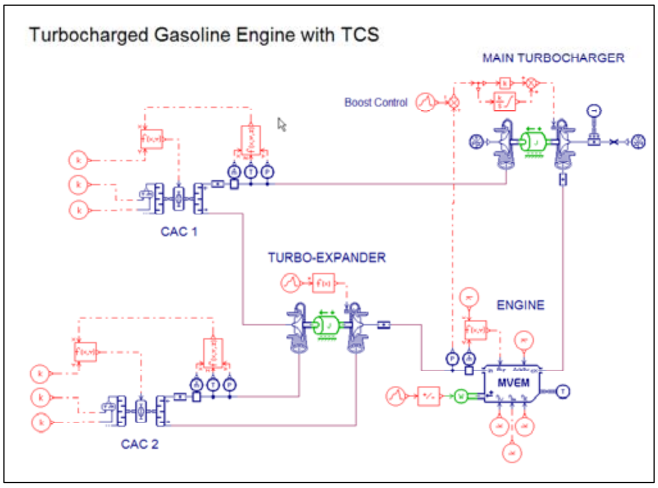

Fig.3: AMESim model: Turbo-Cooling

Process

The modelling process was to:

- Build a 'Baseline' model', using test data & information from real engines
- Use real turbo-machinery & charge air cooler performance & efficiency data
- Fix the engine speed (6000 rev/min)
- Set the nominal power of the engine as 110kW; equivalent to a 2.0 litre normally aspirated engine
- Calculate the Baseline engine performance up to 150kW

- Calculate the TCS engine performance over the same power range
- Operate over the target power range by varying the main turbine area in response to a manifold pressure demand signal

Results

The results of the study are shown in Figs.4 to 9, & will be presented & discussed in sequence

Fig.4 shows the engine charge air intake (manifold) temperature for both engine configurations. For the Baseline engine, manifold temperature is 54ºC at 110kW, rising to 68ºC at 150kW. A larger CAC would partially mitigate this, but with diminishing returns in package size. For the TCS build, the manifold temperature is nearly constant, at 30ºC, as boost pressure and power increase. With appropriate matching and/or use of a bypass, rising or falling manifold temperature can be delivered with increasing boost pressure.

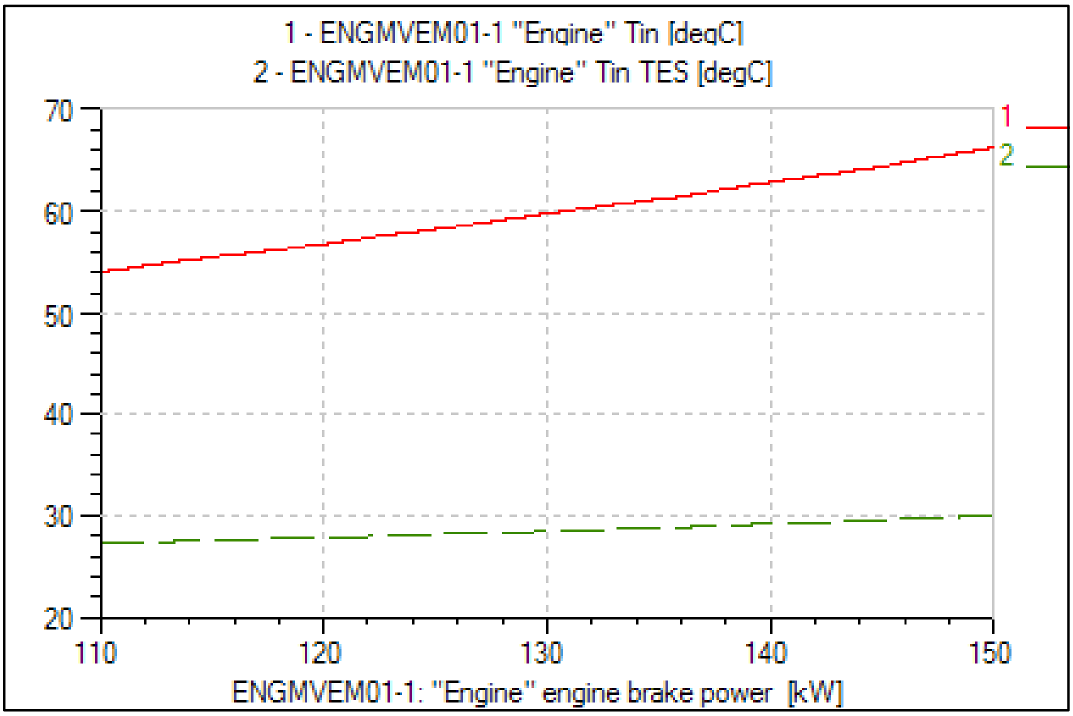

Fig.4: Engine Intake (Manifold) Temperature

Engine intake & exhaust manifold pressures are shown in Fig.5. For a given power, the TCS intake pressure is lower & the exhaust pressure higher than the Baseline engine. The greater pressure difference across the TCS engine increases pumping work (see below, Fig.6).

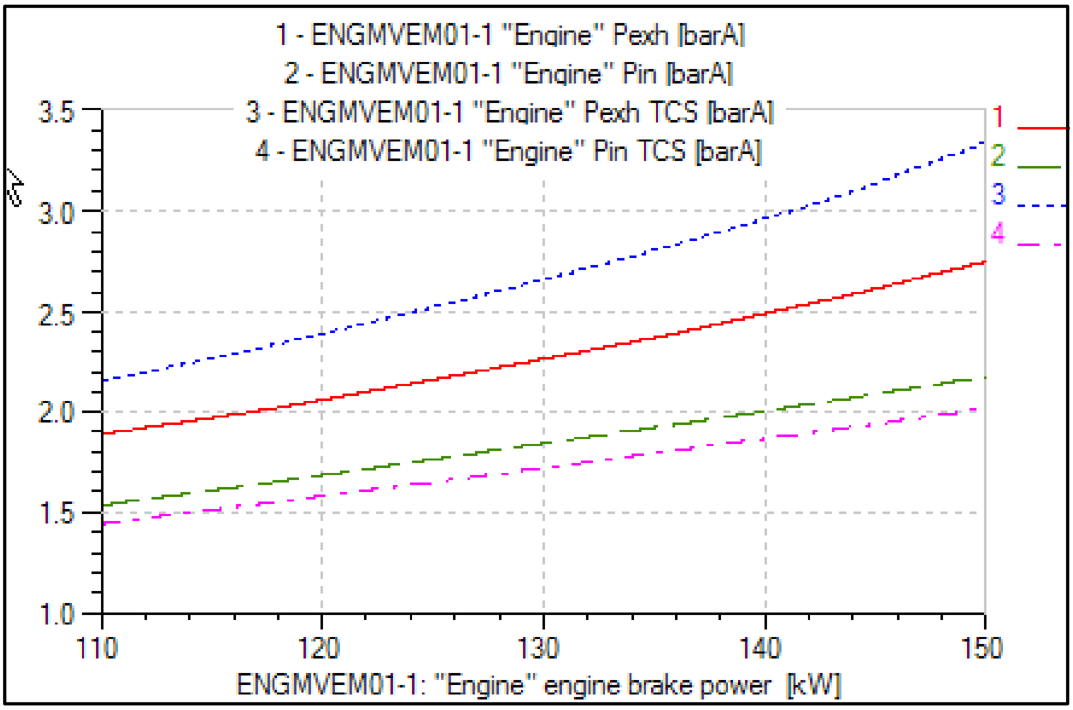

Fig.5: Engine Intake (Manifold) & Exhaust (Pre-turbine) Pressure

The main turbine power & engine pumping losses are presented in Fig.6. At 150kW, the TCS main turbine power is approximately 50% greater than the Baseline, clearly indicating the source of additional energy required to maintain low intake air temperatures. The pumping loss also rises from under 5kW to over 10kW. It should be noted that pumping power is included in the 'mean-value' engine net power.

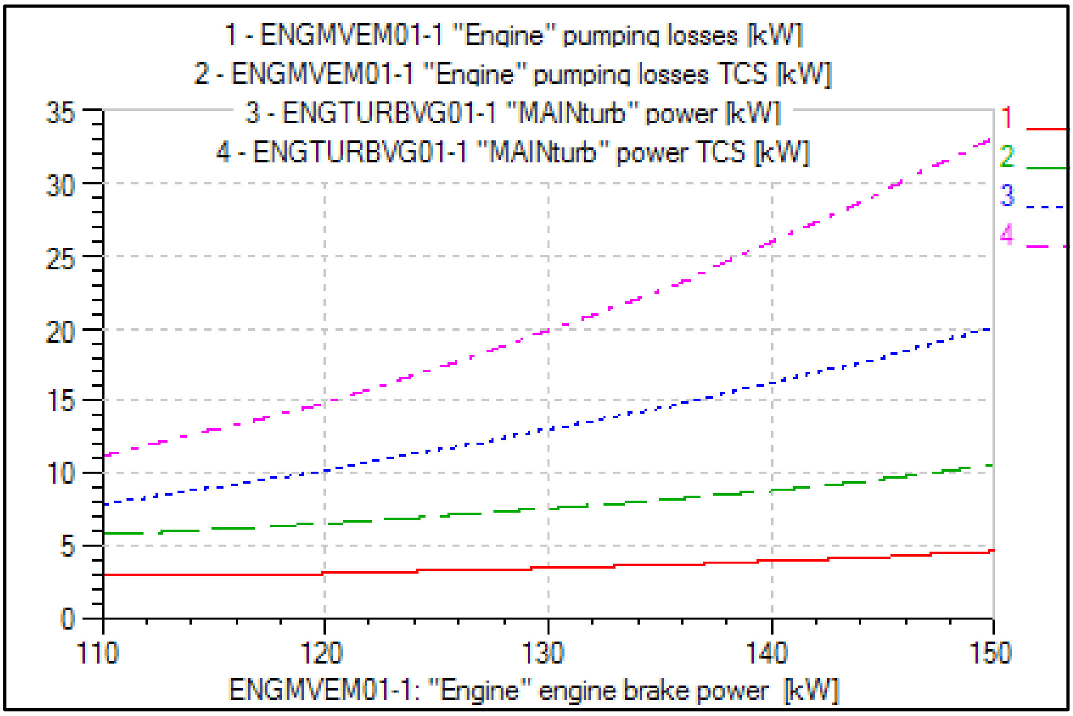

Fig.6: Main Turbine & Engine Pumping Power

Fig.7 shows the pressure ratios of the Baseline & TCS main turbocharger. The performance of these components is based on production performance maps. Fig.7 clearly indicates the increased pressure ratios of the TCS main turbocharger compressor & turbine, but these do not reach extreme levels. Not shown in the figure, the TCS turbo-expander pressure ratios are approximately 1.1:1 & 1.4:1 for the compressor & turbine respectively.

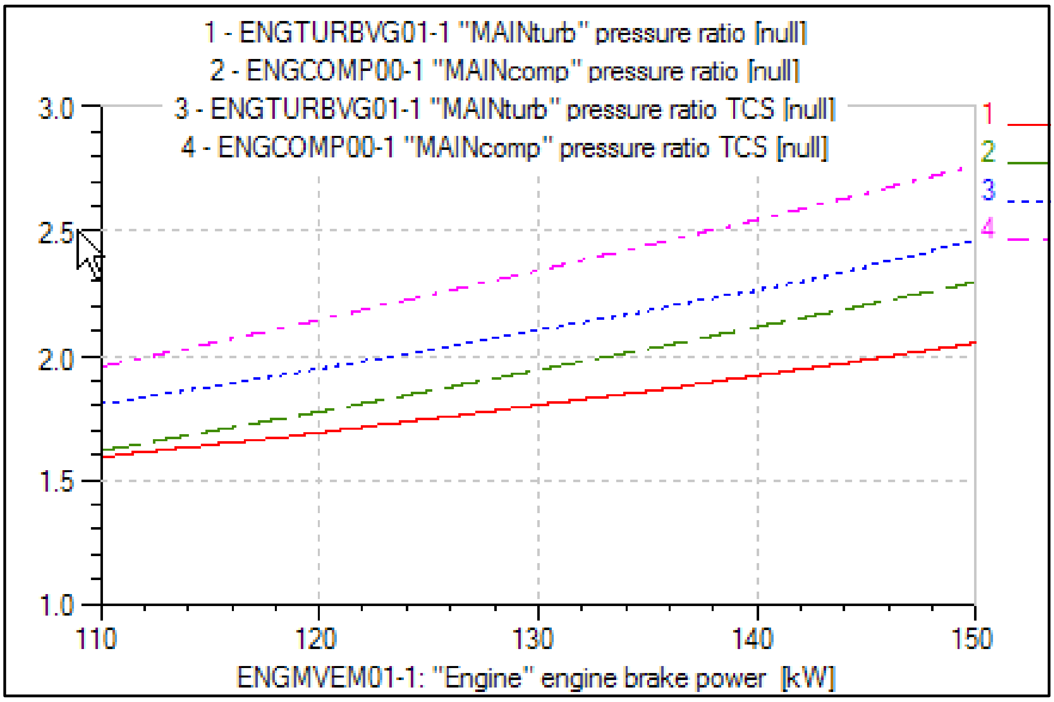

Fig.7: Main Turbocharger Pressure Ratios

In Fig.8, the temperature of the charge air throughout the complete TCS intake system is shown. The ambient temperature (1) used throughout the study is 27°C.

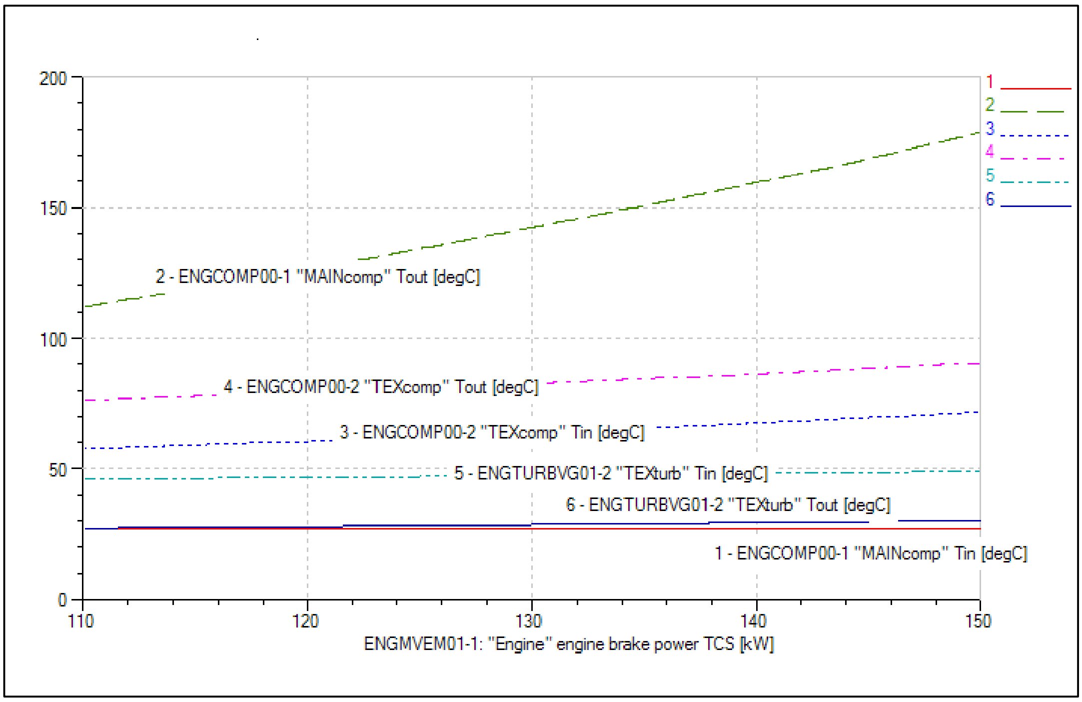

Fig.8: TCS System charge Air Temperatures

Charge air from the main compressor (2) is cooled by CAC1 before entering the turbo-expander compressor (3). The temperature rises during compression to (4), and is then cooled again before entering the turbo-expander turbine (5). Expansion through the turbine further reduces the temperature (6) before the charge air enters the engine. Because the turbo-expander power increases as mass flow rises, the cooling effect automatically increases as engine power rises.

Compressor powers and CAC heat rejection for the TCS system is illustrated in Fig.9.

Heat rejection from CAC1 (2) is significantly less than the heat input represented by the compressor power (1). The temperature rise imparted by the secondary compression in the turbo-expander compressor enables more of this heat to be rejected in CAC2, as represented by the difference between CAC2 heat rejection (4) and the turbo-expander compressor power (3). It is worth noting that, within the turbo-expander, the heat rejected from the air approaches twice that of the power absorbed, thus providing a ‘coefficient of performance’ of approximately 2:1.

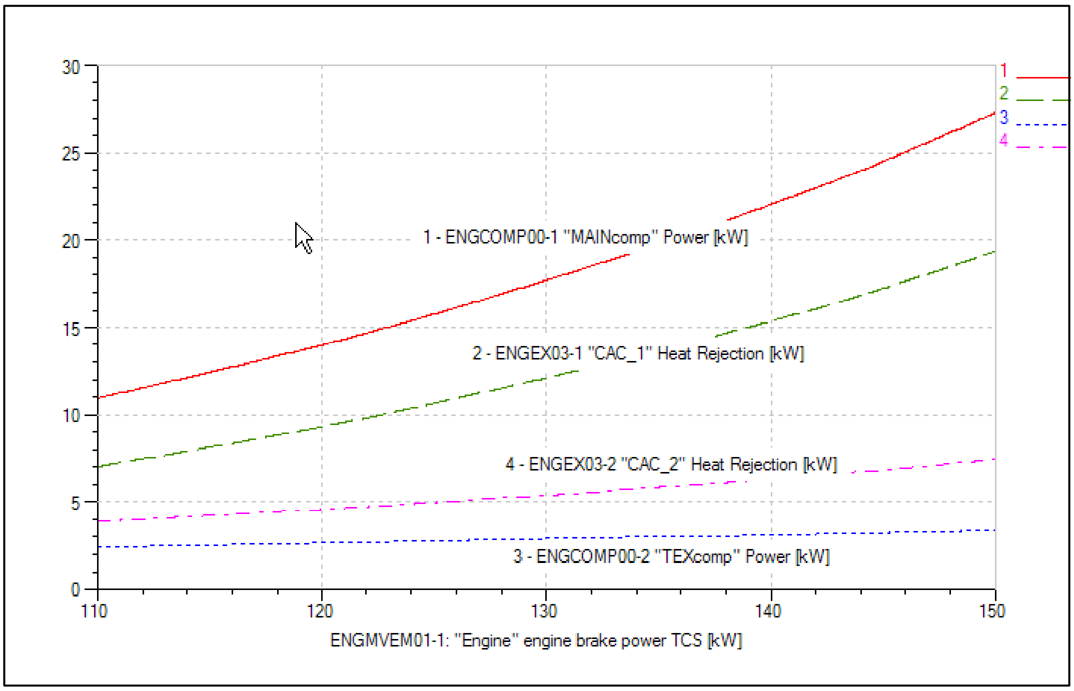

Fig.9: Compressor Power & CAC Heat Rejection

The results of the study are summarised in Table.1 below. The effect of TCS operation is highlighted by comparing the Baseline engine at a ‘production’ power of 110kW, & then increased to a maximum of 150kW. The Baseline & TCS engine performance at 150kw is then compared.

There are 2 versions of the TCS modelling conditions. TCS2 uses the same equivalence ratio as the Baseline engine at 150kW. TCS3 has the equivalence ratio reduced to match the pre-turbine temperature of the Baseline engine. This is a simple way of illustrating the potential to reduce fuel enrichment with a TCS system, due to reduced thermal loading. The air intake temperature remains low regardless.

Table.1: Baseline & TCS Engine Performance

	Build	Baseline1	Baseline2	TCS2	TCS3
Engine					
Engine Speed	(rev/min)	6000	6000	6000	6000
Brake Power	(kW)	110	150	150	150
Brake Torque	(Nm)	175	238	238	238
Equivalence Ratio	(-)	1.17	1.17	1.17	1.13
BSFC	(g/kWh)	334	337	350	339
Inlet Manifold Density	(kg/m³)	1.62	2.23	2.32	2.31
Pumping Loss	(kW)	2.9	4.5	10.5	10.4
Inlet Manifold Temperature	(ºC)	54	66	30	30
Exhaust Manifold Temperature	(ºC)	945	952	933	951
Inlet Manifold Pressure	(barA)	1.5	2.17	2.02	2.01
Exhaust Manifold Pressure	(barA)	1.88	2.73	3.33	3.31
Main Turbocharger					
Compressor Pressure Ratio	(-)	1.6	2.29	2.76	2.76
Turbine Pressure Ratio	(-)	1.58	2.04	2.46	2.43
Turbine Power	(kW)	7.6	19.9	27.2	27.3
TCS Turbo-expander					
Compressor Pressure Ratio	(-)	NA	NA	1.11	1.11
Turbine Pressure Ratio	(-)	NA	NA	1.42	1.42
Turbine Power	(kW)	NA	NA	3.35	3.35
CAC1					
Air Inlet Temperature	(ºC)	87	142	178	178
Air Outlet Temperature	(ºC)	54	66	72	72
Heat Rejection	(kW)	4.2	13.1	19.2	19.2
Effectiveness	(-)	0.79	0.78	0.79	0.79
CAC2					
Air Inlet Temperature	(ºC)	NA	NA	90	90
Air Outlet Temperature	(ºC)	NA	NA	49	49
Heat Rejection	(kW)	NA	NA	7.4	7.4
Effectiveness	(-)	NA	NA	0.82	0.82

EXPERIMENTAL PROGRAMME

At the time of writing, work has commenced on a rig-based experimental programme. The overall aims are to demonstrate the performance of the turbo-expander & generate input data for design of a dedicated expander & for overall engine performance matching. The approach is based on the work performed by the author in the mid-1980s, for Formula 1 engine development.

A standard production diesel turbocharger has been procured & mounted into a special test rig. The main components of the rig comprise:

- Independent high boost air supply, with fully variable flow, pressure & temperature
- Air pre-cooler (air-cooled vehicle charge air cooler)
- Turbocharger, forming the turbo-expander unit
- Intercooler mounted between turbocharger compressor outlet & turbine inlet (air-cooled vehicle charge air cooler)
- Outlet throttle, for overall flow control

Fig.10 shows the rig installation with the major components as described above. At the time of writing, preliminary testing has commenced. The test programme & data analysis will form the basis of a future publication.

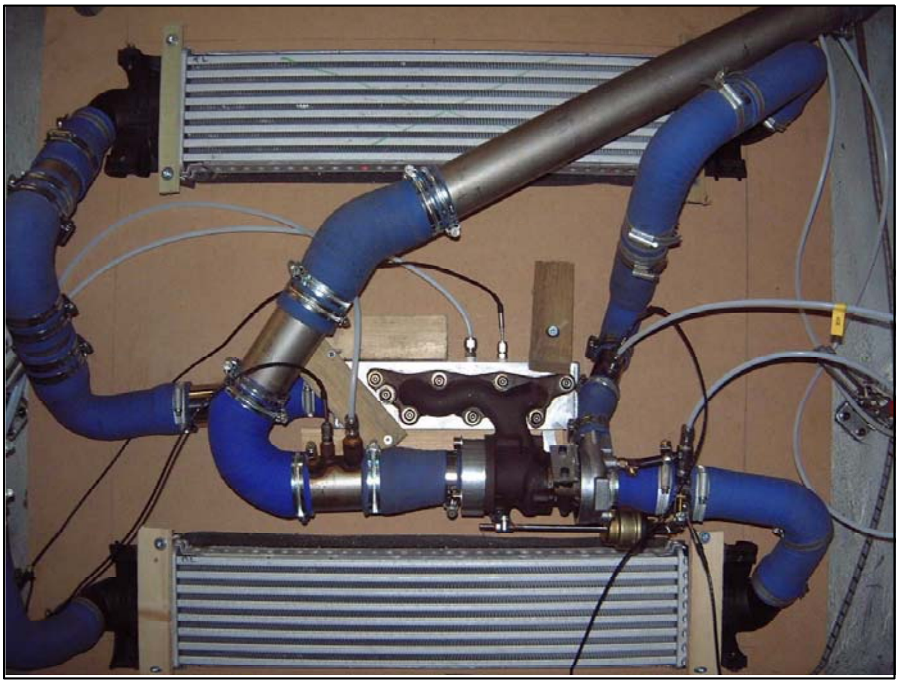

Fig. 10: Experimental Turbo-Expander Test Rig

APPLICATIONS, PRODUCTION & INTEGRATION

This preliminary study has indicated potential production applications of a modern turbo-cooling system; some of these options are discussed below.

Applications

The case study, a downsized turbocharged gasoline engine, showed the potential for useful power increases with reduced intake manifold temperature. The next steps for this type of application would be to investigate the effects of:

- High load EGR: an increasing area of investigation to improve combustion stability & reduce fuel enrichment.
- Improved fuel economy at high speed cruise: lower intake temperatures reduce thermal load & improve the detonation margin, thus reducing the fuel enrichment requirement
- ‘Low Pressure’ EGR routing: in the extreme case of turbo-expansion, the post-turbine pressure in a vehicle system is higher than the intake manifold pressure. This allows an EGR route from the turbine exit to the engine intake manifold, with consequential benefits from gas temperature reduction & increased turbine work.

Using the basic principles & thermodynamics of turbo-cooling, other engine applications worth investigating include:

- Light duty diesel: Increased specific power due to more favourable intake air pressure/temperature trade-off, plus improved high load EGR operation for light commercial vehicles
- Heavy duty diesel: High load EGR flows can be increased due to the reduced charge temperature & more favourable pressure gradient across the engine

- HCCI/CAI operation & combustion mode transition: Precise & accurate modulation of charge air temperature by VG control of turbo-expander and/or controlled bypass operation

Production

The system design principles are based on current turbo-machinery & charge air coolers. Recent developments in electrically powered ‘boost-augmenters’ (e-Boosters) have shown the potential for a compact lightweight turbo-expander. These design principles would allow the construction of a turbo-expander with the following features:

- Low pressure ratio
- Lightweight materials (aluminium & plastic)
- Sealed bearings (rolling contact or air type)

Integration

The turbo-expander comprises an independent system that can be added onto the existing powertrain installation. Subject to charge air cooling requirements, location & packaging within the vehicle are flexible. There is little or no impact on the external arrangement of the base engine, which makes the turbo-expander a simple add-on system.

Beyond this simple & cost effective concept design, further enhancements could be made, namely:

- Integration with the second charge air cooler, by direct mounting on the header tank of the cooler
- Integration with e-booster components & design. This is an interesting opportunity to improve both low speed torque & high speed power with the same system. Conceptually this device will be as shown in Fig.11. The figure clearly shows the compressor, electric drive motor & turbine. This concept would require a ‘downstream’ e-Booster design, with sealing to contain the air pressure from the main turbocharger compressor
- Inclusion of a bypass circuit to allow close control of intake conditions.

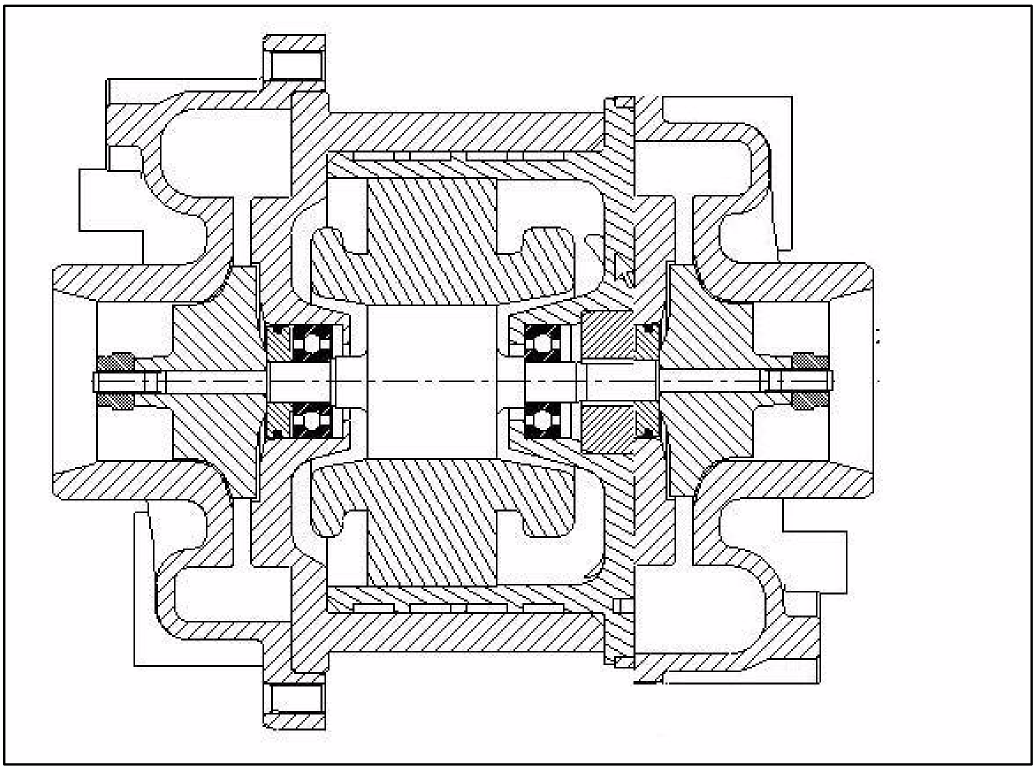

Fig. 11: Combined Turbo-Expander/e-Booster Concept

CONCLUSIONS

The aim of this study has been to investigate the potential for the application of turbo-expansion to meet the needs of modern vehicle engines. The various potential applications, benefits & opportunities have been reviewed. The case study, on a downsized gasoline engine, has quantified the performance differences between TCS & standard turbocharging as power levels increase.

The case study confirms the basic feasibility of TCS application to a modern engine; specifically the ability to reduce intake pressure & temperature at increasing engine power. The exploitation of these effects is well understood in principle & now requires validation on a real engine.

The thermodynamic & fluid flow results from the case study have also indicated potential for emissions & EGR flow/cooling opportunities at high engine loads on diesel & gasoline engines.

NEXT STEPS

Building on the authors' experience & this initial study, a range of activities are planned to further investigate & develop the potential of a modern TCS system. These include:

- Completion of the preliminary rig test work
- Further gasoline engine modelling using specific engine geometry & a 'full-feature' model
- Application studies on light & heavy duty diesel engines, concentrating on emissions reduction
- Motorsports applications for intake restricted gasoline & diesel engines
- Concept & detail design of a dedicated turbo-expander unit

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