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Active Charge Cooling

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ABSTRACT

Boosted IC engine development, both diesel and gasoline, is driving the need for better charge air temperature control. Charge air temperature directly and indirectly influences engine performance, fuel economy & emissions. To date charge air temperature control has, in the main, been passive; aiming only to reduce temperatures towards, but still above, ambient temperature. Driven by increasing specific output, the opportunities for sub-ambient charge cooling need to be investigated. For some real world driving conditions it is also desirable to raise the charge temperature.

Air Cycle Technology ltd (ACT), working with the University of Huddersfield (UoH) are developing a controllable charge air cooling system, which will deliver charge air at sub-ambient temperature over a wide engine operating range. The system uses a turbo-expander to deliver air-cycle cooling in a simple and practical way. The system can be enhanced by combination with a charge air heating process. Accurate charge temperature control over as wide an engine operating range as possible is also addressed. The system is fully compatible with the operational, packaging and cost needs of vehicle OEMs.

The paper presents the principle, process and application of a controllable charge air cooling/heating system. It covers the design and operation of the turbo-expander which delivers sub-ambient charge temperatures, the option of charge air heating and possible control methods. Examples of specific engine applications are presented to clearly indicate the opportunities for improvements in engine performance and fuel economy.

INTRODUCTION

The use of charge air cooling using turbo expansion techniques was first developed in the 1950s (1) and one of its first applications was during the 1960s in prevention of detonation in natural gas engines caused by the variability in fuel properties (2). Over the 50 years since then, the principle has been revisited several times, for racing applications (3, 4) as well as road vehicle powertrains where a study (5) showed that the application of charge cooling for emissions improvement on medium and heavy-duty diesel as well as gasoline engines was feasible.
Current legislation demanding improved fuel economy and emissions has reinvigorated interest in the technology, and more recent theoretical studies demonstrated that there were significant benefits to be gained when applying charge cooling to downsized boosted gasoline engines. It was shown that a charge air temperature reduction of over 30 degrees C could be achieved without fuel penalty (6).
Further work (7) delivered a working prototype turbo-expander, based on production turbocharger design and manufacturing technology. The design was

validated by rig testing and the target performance and efficiency was achieved. The prototype has been installed on a demonstrator vehicle and is continuing to amass durability data.
Although cooling charge air as a principle has been demonstrated to have advantages, there are also associated disadvantages. Overcooling of the air can result in ice formation in the intake, with potential for catastrophic effects if this is ingested into the engine. A more optimal solution would be to provide air at a constant temperature to the engine intake, and that is the objective of this work.

PRINCIPLES OF CONTROLLABLE CHARGE AIR COOLING AND HEATING

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

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

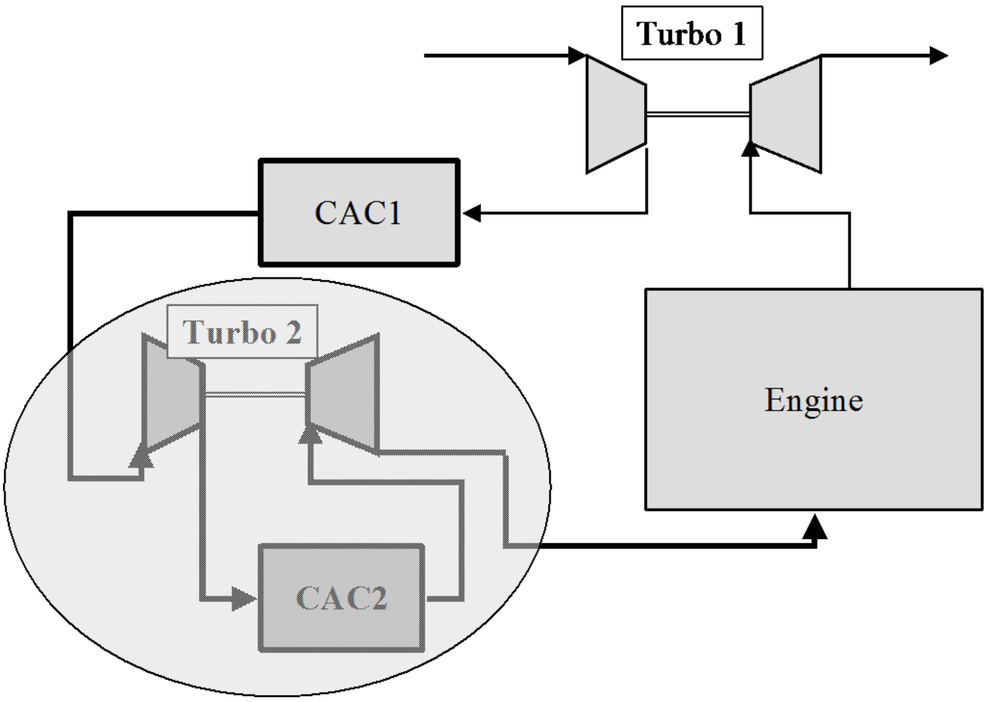

Figure 1: Turbo-Cooling concept Layout and Gas Flowpath

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 and expansion is compensated for by increased work in the first compressor. The net effect on the engine is increased exhaust pressure into the main turbine.

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

Any turbocharged engine can benefit from turbo cooling, although the range of potential benefits varies with both the combustion type and the application. The key principle is to combine increased intake charge density coupled with reduced charge air temperature. Using conventional boosting systems, these tend to be contradictory, with air temperature rising with increased boost pressure. It is also not possible to reduce the charge temperature to below that of the ambient air using either air to air or air to water heat exchangers. Reducing the charge air temperature offers benefits relating to output, detonation, thermal loading and emissions, whilst offering additional control over combustion rates and cylinder pressures.

It has been shown previously (7) that it is possible to supply charge air to the engine at over 30 deg C below the temperature that the system without the turbo expander would achieve. However, from a combustion control perspective, a more consistent inlet temperature would be preferable.

PROCESS

Given that the turbo expander unit can provide a supply of cool air, it is then possible to control the temperature of the intake air by a variety of means. The cool air can be mixed with warmer air from the turbocharger compressor, or could be warmed directly using heat from elsewhere as shown in figure 2.

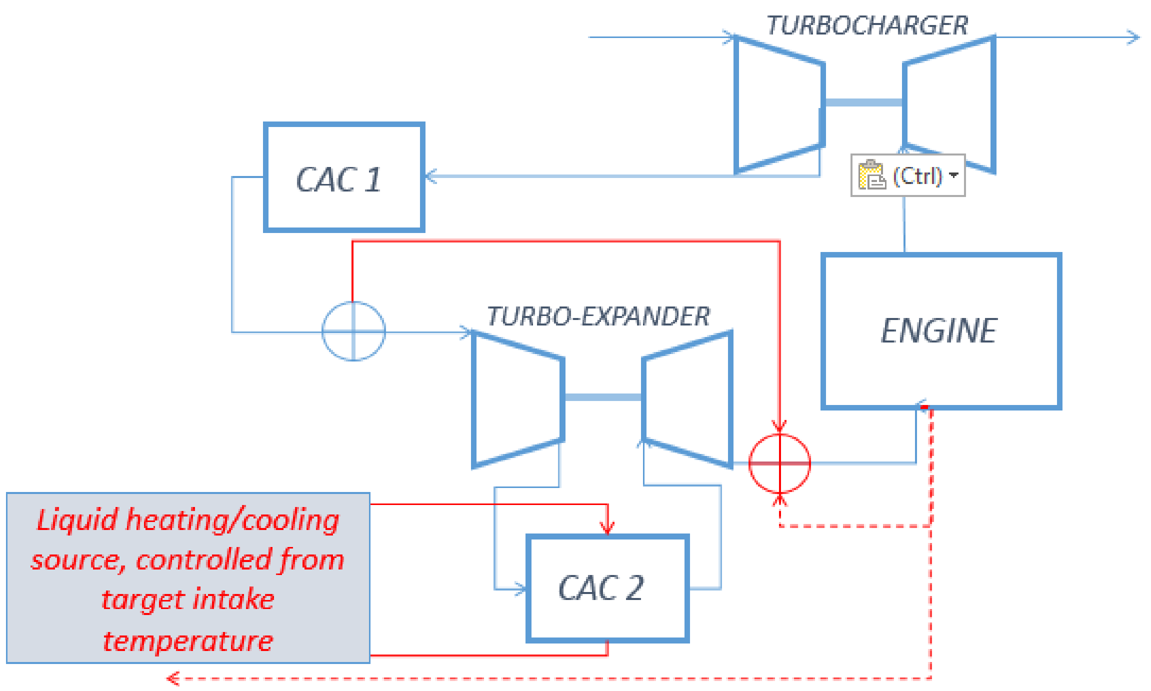

Figure 2: Temperature controlled concept Layout and Gas Flowpath

In this way, the temperature of the intake air can be managed to provide optimum conditions for combustion across a range of operating conditions. For example, the air could be heated under cold startup conditions to decrease engine warmup time, hence reducing emissions on startup. Conversely, when running under high load conditions, cooled air can be used to reduce combustion temperatures and prevent knock as an alternative to overfuelling, therefore reducing fuel consumption as well as emissions.

Requirement and Application

The opportunity for air heating is available in conventional charge cooling systems, either by charge air cooler (CAC) by-pass at high load or engine coolant heating transfer within the CAC to raise temperatures. These techniques are coming into use, driven by the need to minimise condensation in intake systems resulting from high EGR levels, particularly with low pressure loop systems.

The significant advance presented here is the application of charge air 'refrigeration' using air-cycle cooling (ACC), and the study concentrates on this aspect of ACC. The dominant technical driver is the combustion limitation on the increase of specific output in increasingly highly boosted gasoline engines. As specific outputs rise, detonation becomes the major limitation. The predominant mitigation techniques are ignition retardation combined with excess fuel input, and ultimately compression ratio reduction. Ignition retardation and excess fuelling are inseparable; the retardation reduces detonation but reduces combustion efficiency and increases exhaust temperature and thermal loads on critical components. Fuel is added, above the combustion requirement, to limit the exhaust temperature increase. This technique is acceptable in full load operation outside normal driving, but as engine capacities reduce, vehicles are spending greater proportions of real-world drive cycles at high load, with consequent significant increase in total fuel consumption. Similarly compression ratio reduction to limit detonation impacts on fuel economy at all load-speed conditions.

Charge air reduction has been shown to clearly reduce detonation (INSERT REF) so the opportunity to cool the charge air below the 'passive' charge cooling limits offers a significant potential to enable increases in specific outputs and minimise fuel consumption penalties (INSERT REF)

System and Operation

The system is based on the schematic shown in Figure 2. The core element is the turbo-expander which delivers the charge air temperature drop by expansion. The efficiency of the turbine, and to a lesser extent the compressor, is critical to the overall performance of the system. There is an energy loss through the cooling process, which reduces charge density at exit from the turbo-expander; this is compensated for by an increase in primary boost from the engine turbocharger, so component efficiency becomes critical. The ACC turbine efficiency is 85% at the design point and above 80% over a wide operating range.

Modelling

The AMESim 1D modelling platform is used extensively to support system and components performance prediction. At the component level ACT have developed a 1D turbine design and performance prediction 'module' running within AMESim. This has been validated in previous studies (INSET REF) and supports integration of 'dynamic' turbine performance within the ACC system. The ACC system has bene modelled both to correlate with rig testing (INSERT REF) and then to predict the potential for charge temperature control for specific engine applications.

Figure 3 shows a 1D engine model incorporating the charge air refrigeration components of ACC. The turbo-expander and its associated charge cooler are inserted between the main CAC and the engine intake manifold. The ACC application is very simple; the entire engine air charge passes through the turbo-expander and its cooler, resulting in uncontrolled charge air temperature reduction.

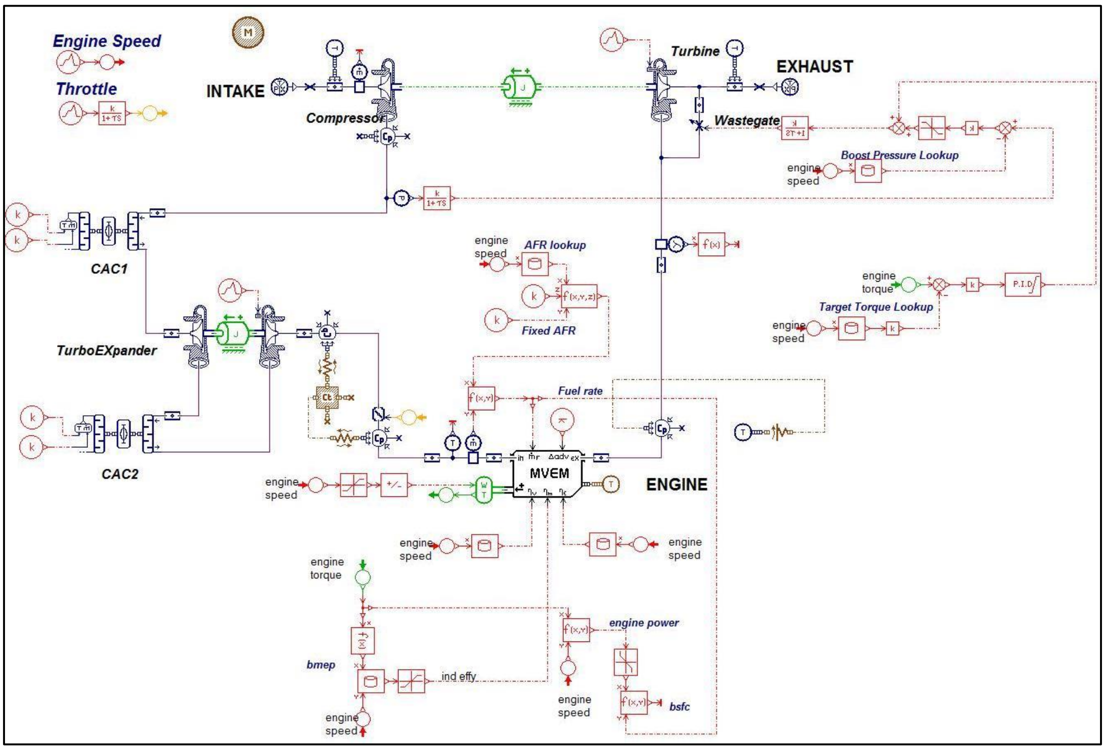

Figure 3: 1D system model with uncontrolled ACC

The engine chosen for the modelling example is a 1.6 litre 4 cylinder gasoline, normally rated at 240 Nm and 140 kW. To emphasise the potential of ACC the BMEP has been increased over the speed range to achieve 330 Nm and 158 kW maximum torque and power. This is the practical limit using the standard turbocharger. The enhanced torque curve is shown in Figure 4.

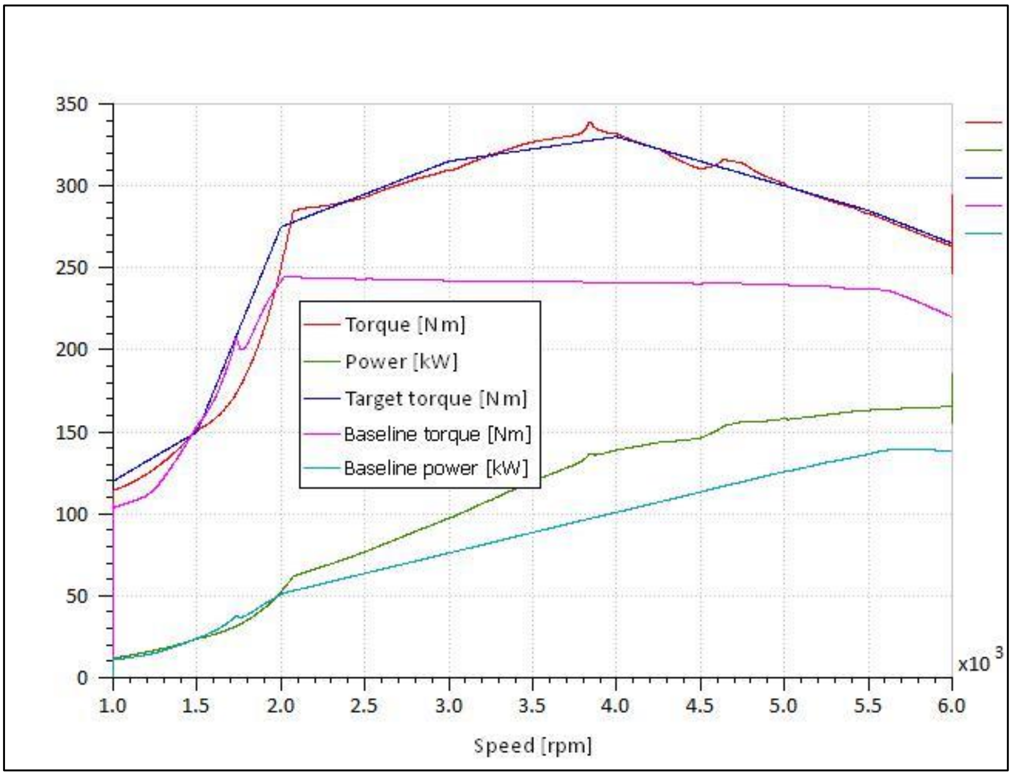

Figure 4: Performance at WOT over speed range

Figure 5 shows the key charge air temperature over the speed range; namely the temperature out of the primary charge air cooler (CAC1) and in the intake manifold, at exit from the turbo-expander turbine.

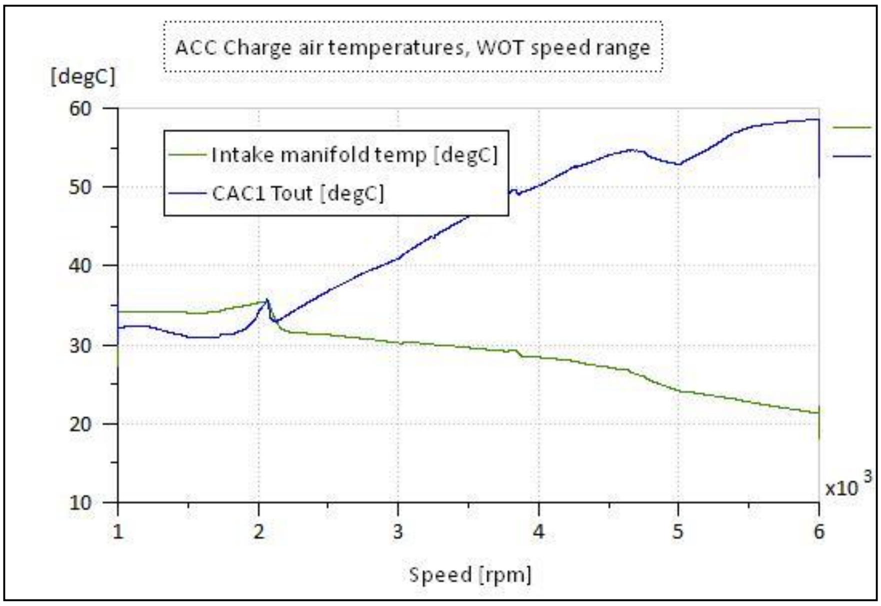

Figure 5: Charge air temperatures with baseline ACC, WOT sped range

Significant air temperature reductions are achievable; the manifold temperature at maximum engine speeds being approximately 35 degC. lower than at the main charge cooler exit. As mentioned above, the temperature reduction is uncontrolled, and increases with engine speed; at low engine (and turbo-expander) speed the mass flowrate though the turbo-expander is insufficient to generate useful pressure ratios, so no temperature reduction takes place.

A practical ACC system clearly requires a degree of air temperature control in order to optimise the engine performance in response to varying ambient and boost-related air temperatures. In the simplest form this can be achieved by diverting air from the main CAC around the turbo-expander & mixing it with the turbo-expander exit air. This can use a control system, discussed below, which aims to deliver air a target temperature at the intake manifold.

Figure 6 shows a local section of the 1D system model with a simple by-pass loop added.

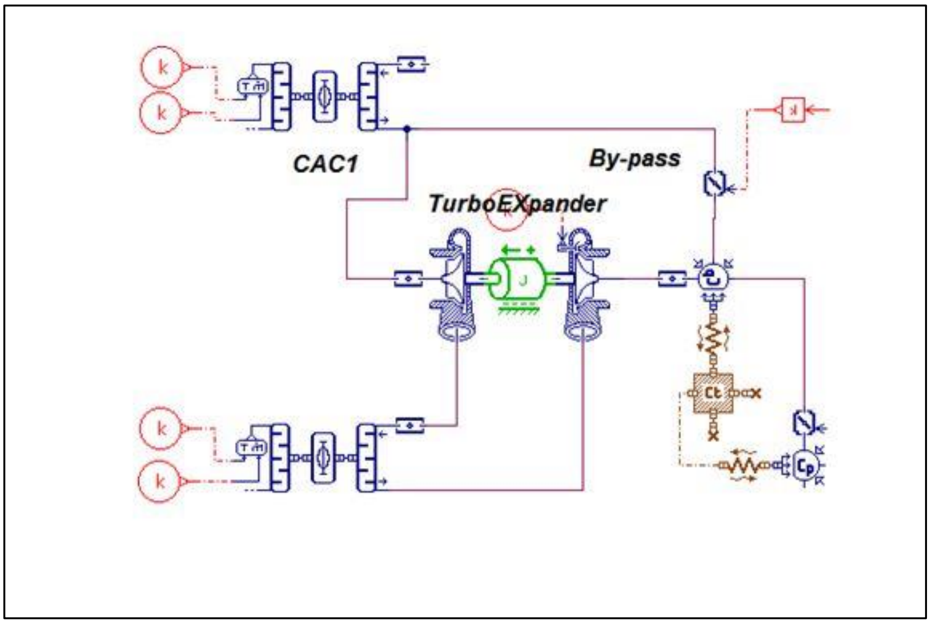

Figure 6: ACC by-pass flow path

The impact on air temperature of the by-pass system is shown in fig. 7.

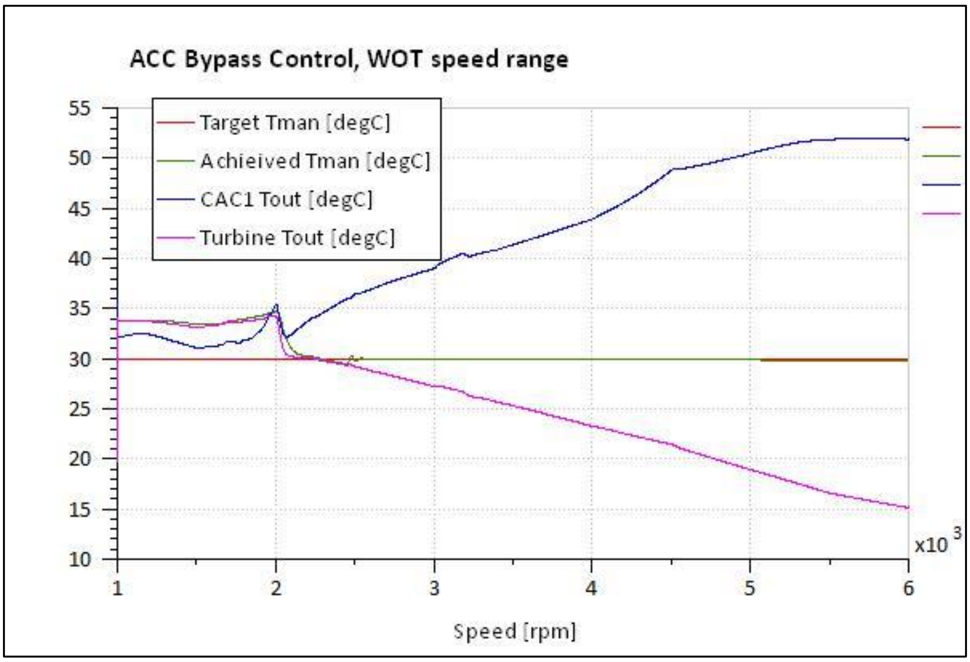

Figure 7: Key system temperatures with by-pass system operating

In the model the target intake manifold temperature (Target Tman) has been set at 30 degC. Over the engine speed range above 2000 rpm, the by-pass control system modulates the air flow to maintain the target temperature, producing up to a 33 degC temperature reduction relative to the exit temperature the main charge air cooler (CAC1). The exit air temperature from the turbo-expander falls to approximately 15 degC. Below 2000 rpm, there is insufficient air flow for the turbo-expander to provide effective cooling. This is not considered to be a major issue in the context of real-world driving. ACT are working on more sophisticated controls systems which will extend the envelop of effective of temperature control

Control Strategy

The objective is to control manifold temperature when both the ambient temperature and the boost related temperature rise are varying under driving conditions.

At a given driving condition there will be a desired manifold temperature; examples being to reduce warm-up time, optimise combustion or minimise mechanical friction or emissions. The desired temperature could be higher than the 'available' un-cooled boost temperature or lower than the 'achievable' cooled boost temperature. With current charge cooling systems these limits are either 'hot' by-passing the main charge air cooler or 'cold' by fully charge cooling, (which in turn is a function of the ambient temperature).

The control strategy for active charge cooling is therefore based on achieving a target intake manifold temperature over the widest possible speed-load envelope of the engine, which may either be hotter or colder than that achieved by the passive cooling typical of current systems.

The approach is to utilise engine coolant temperatures to raise the charge air temperatures and air cooling turbo-expansion to extend the limits of a passive system.

The strategy can simply be a control loop based on the error between a measured temperature in the intake manifold and a target temperature, stored in the ECU, which could typically be a function of engine/vehicle speed and load. This has been presented for WOT operation in the modelling study above. It may also be desirable to provide effective temperature control under part-load conditions in relation to, for example, EGR temperature management, combustion stabilisation or emissions control.

Vehicle demonstration

A prototype ACC system has been fitted to a gasoline engine passenger car, for the purposes of demonstrating the basic principles and typical results achievable. The C/D class car has a 1.8 litre 4 cylinder turbocharged engine, generating a maximum of 132 kW. The prototype ACC system was installed with minimum modification to the production engine package. In this particular application the turbo-expander charge cooler (CAC2) is liquid cooled, with an independent cooling circuit and front mounted low temperature radiator (LTR). The turbo-expander and charge cooler sub-assembly is shown in fig. 8. This prototype is based on a production turbocharger, with the exhaust gas turbine and housing replaced by the cold air turbine and housing designed by ACT.

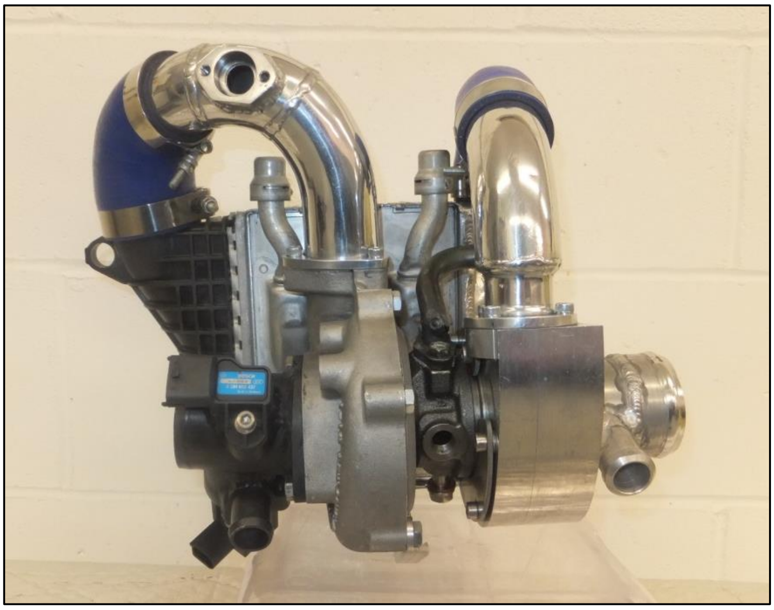

Figure 8: turbo-expander and cooler sub-assembly

The vehicle installation is shown in fig. 9, where the turbo-expander and its charge cooler can clearly be seen. The by-pass was inoperative, and no changes were made to the engine calibration

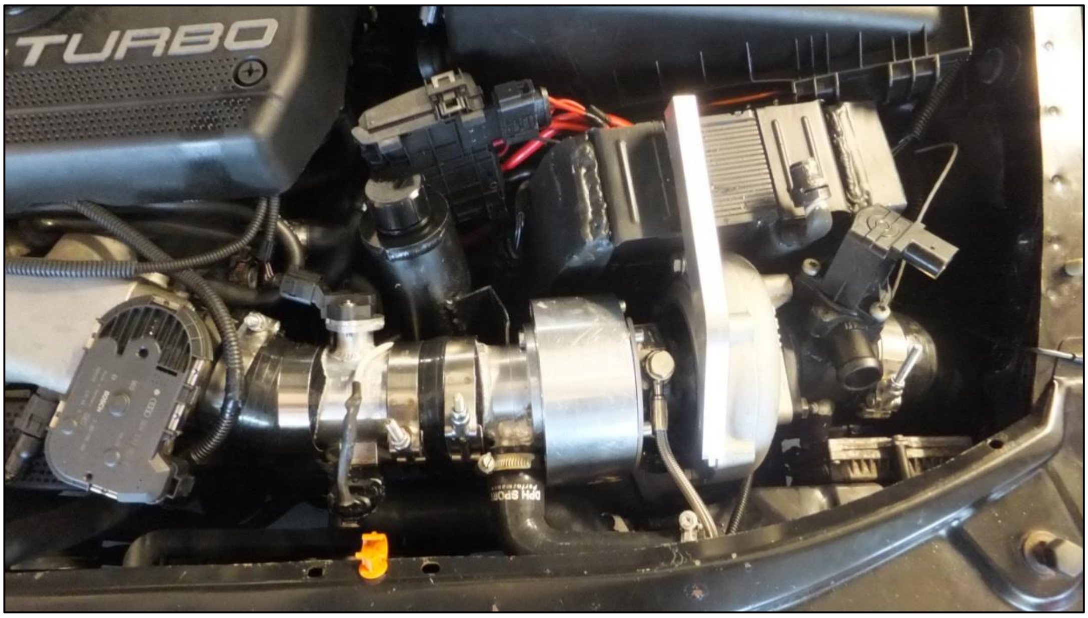

Figure 9: Vehicle installation of turbo-expander

The system was fitted with sensors and a logging system and driven on the road and a test track. High load operation best demonstrates the performance potential of the system and sample results are shown in Fig. 10. The test sample was WOT acceleration through the gears, from 76 to 121 mph vehicle speed. The key temperatures; at turbo-expander (TEX) intake and exit are presented, also the engine air box temperature and the engine and turbo-expander speeds

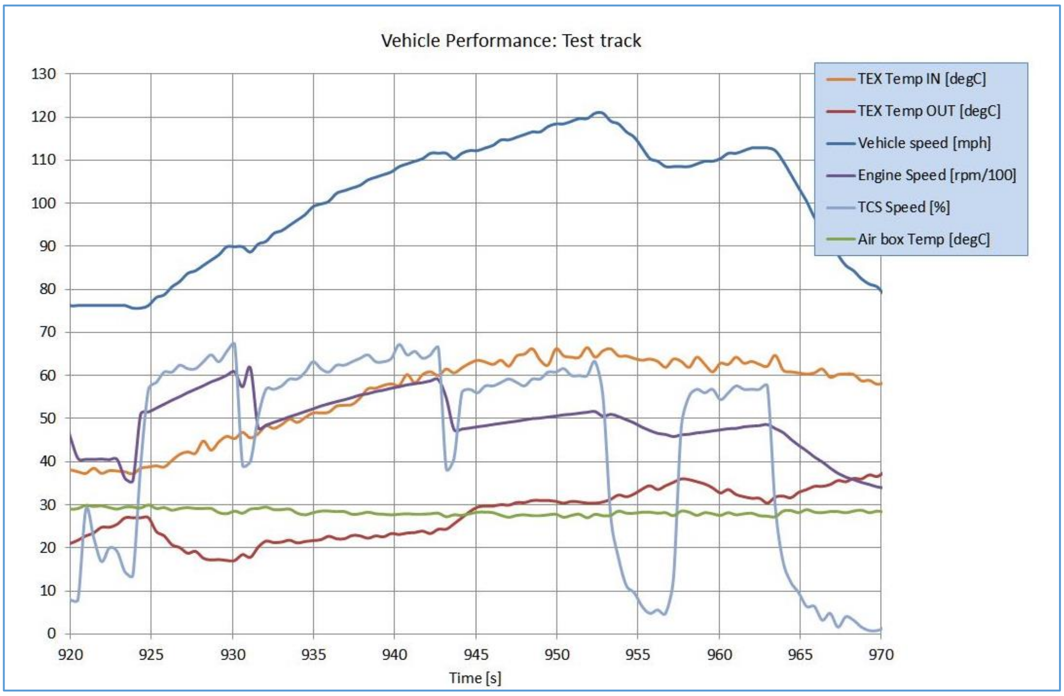

Figure 10: Vehicle performance

The temperature drop through the turbo-expander can clearly be seen, reaching a maximum of 35 degC, which is consistent with the results of the modelling study.

At t = 950 s a TEX intake temperature (same location as CAC1 exit) of 65 degC resulted in an engine intake temperature of 30 degC. Also noteworthy is that during the early part of the acceleration (t= 925 > 945 s), the TEX exit temperature is lower than the engine air-box temperature, confirming that sub-ambient charge cooling is feasible. The TEX shaft speed indicates the excellent transient response of the turbo-expander, which has a low rotational inertia.

Summary

The work presented here has covered the thermodynamic principles of an 'active' charge air heating and cooling system, followed by a more detailed study of charge air cooling to levels below those achievable with current 'passive' systems. The operating principle is the air-cycle refrigeration process. A system comprising a turbo-expander with dedicate cooler and a by-pass loop for temperature modulation, has been developed. 1D engine and charge air system thermo-fluid modelling confirmed the technical feasibility. This led to a prototype turbo-expander being developed, derived from automotive turbocharger technology. This was rig tested then installed on a passenger car demonstrator vehicle. The vehicle testing confirmed the predicted performance, demonstrating significant charge air temperature reductions. Temperature control using a by-pass process has been modelled, and will be tested in the near future.

Conclusion

The potential benefits, in engine performance fuel economy and emissions, of charge air temperature modulation are being evaluated by OEMs, driven by both customer and legislative demands. The potential for moving from 'passive' to 'active' charge air temperature control has been demonstrated by the work presented here. The ability to sub-cool charge air is the most innovative feature of the work, to which the addition of air heating would be relatively simple. Sub-cooling has been achieved with 1D modelling, prototype hardware manufacture and vehicle testing. The potential of the system has been clearly demonstrated. Air-cycle cooling principles have been applied, using a turbo-expander and related charge cooler which are capable of cost-effective high volume production using current automotive processes and even existing components. The development of a high volume product from the prototype work presented here can be carried out quickly with low technical and commercial risk, resulting in a system capable of manufacture by existing automotive Tier 1 suppliers.

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