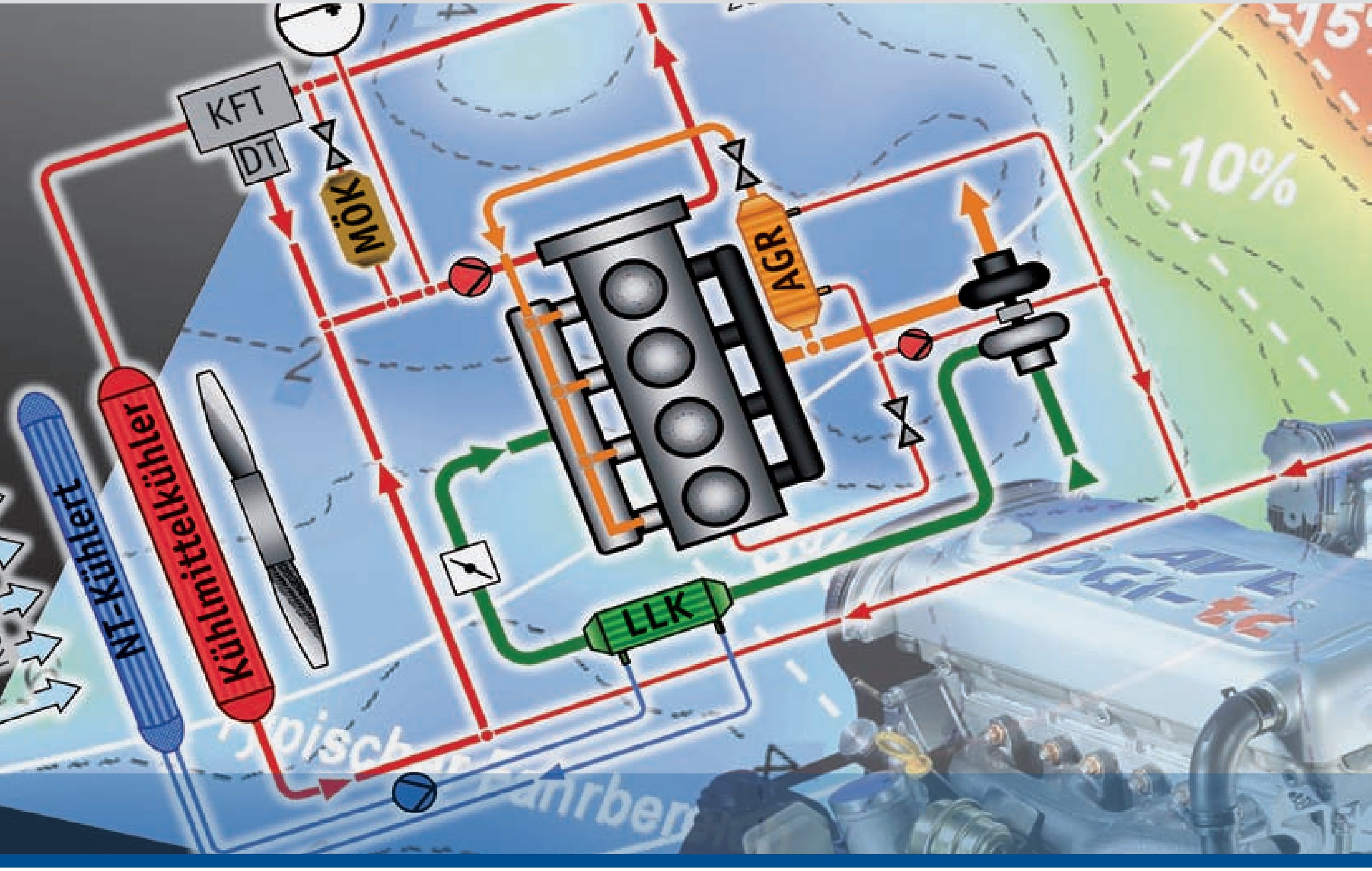

The Reduction of CO_2 Emissions from a Turbocharged DI Gasoline Engine through Optimised Cooling System Control

In a joint project Behr, Behr-Hella Thermocontrol (BHTC) and AVL List have investigated various thermomanagement technologies in order to reduce the CO_2 emissions of a turbocharged direct injection gasoline engine. Through the use of cooled EGR the fuel consumption at part load was reduced by up to 5 %; at full load the consumption was reduced by up to 18 % since no enrichment was needed. Under real driving conditions a saving of 6 % was achieved. A further reduction of about 3 % in the NEDC was possible via coolant stand still during the engine warm-up. Additionally, it was shown that a change in the engine coolant temperature of 10 K, made possible by the application of a map controlled thermostat, has the potential for savings of up to 1.4 %.

1 Introduction

Significant fuel consumption savings can be achieved in gasoline engines through the application of different technologies. One such technology is direct injection, which, when combined with turbocharging, allows the engine to be downsized. However, this means that the engine operating point climbs to a higher load condition, with its associated risk of knock and the requirement for enrichment in order to control component temperatures. Furthermore, such fuel savings must not just be achieved during prescribed test cycles, but also during real world on road driving. Cooled EGR is one of several technologies that have the potential to give such fuel savings. Another such technology is optimised thermomanagement through, for example, coolant stand still during the engine warm-up (relevant for the NEDC) and a load dependent control of the coolant temperature.

2 Cooled EGR and Optimised Thermomanagement

The potential savings were investigated using a 2 litre turbocharged direct injection gasoline engine (rated at 150 kW, with 320 Nm torque between 1500 and 4500 rev/min and a compression rate of approximately 10:1). This basis engine has single stage turbocharging and variable valve timing on the inlet and exhaust (which enables internal EGR). The engine was built in a VW Passat demonstrator vehicle by AVL.

Based upon the engine characteristics an EGR cooler, similar to those currently in production for Diesel engines, was designed and installed. The external EGR was used at intermediate loads (between 5 and 14 bar BMEP) and at full load (up to 4000 rev/min). Two factors determine the design of a suitable EGR cooler: at part load condensation should be avoided in the cooler in order to prevent fouling of the cooler and valve; at full load the maximum EGR rates are determined by the coolant flow rate (to prevent boiling) and the cooler size (for maximum cooling).

In **Figure 1** the coolant circuit layout is shown. For the initial investigations on the engine test bed the EGR cooler was independent of the engine cooling circuit. In the vehicle the EGR cooler was arranged in a cooling sub-circuit together with the turbocharger. The coolant for the EGR cooler was taken from the engine block and returned before the water pump. In the place of the standard thermostat a map controlled thermostat (MCT) was fitted which has an integrated throttle thermostat together with a bypass. Electrical valves in the cooling sub-circuits for the engine oil cooler and cabin heater were added. The coolant flow in those sub-circuits was controlled via those valves during the main circuit coolant stand still. The arrangement of the coolant sub-circuit for the EGR cooler and turbocharger also allowed cooling during engine warm-up (coolant stand still) – this coolant flow was controlled by a separate valve.

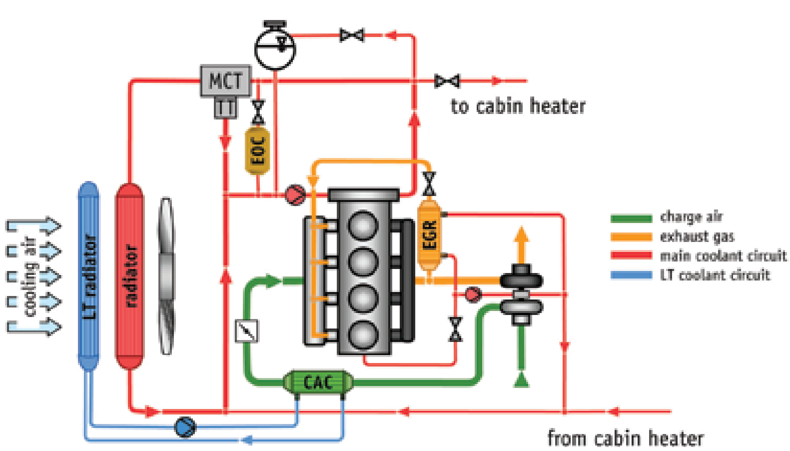

Figure 1: Layout of the cooling circuit

The Authors

Dr. Simon Edwards
is Head of the Engine Cooling Deveopment at Behr GmbH, Stuttgart/Germany.

Dipl.-Ing. Rolf Müller
leads the Engine Technology Department within Advanced Engine Cooling Development at Behr GmbH.

Dipl.-Ing. Georg Feldhaus
leads the project „Cooled EGR for SI Engines" within Advanced Engine Cooling Development at Behr GmbH.

Dipl.-Ing. Thomas Finkeldei
is Development Engineer in the Advanced Development of BHTC GmbH, Lippstadt, Germany.

Dipl.-Ing. (FH) Matthias Neubauer
is Development Engineer in the Business Unit SI Engines of AVL List GmbH, Graz, Austria.

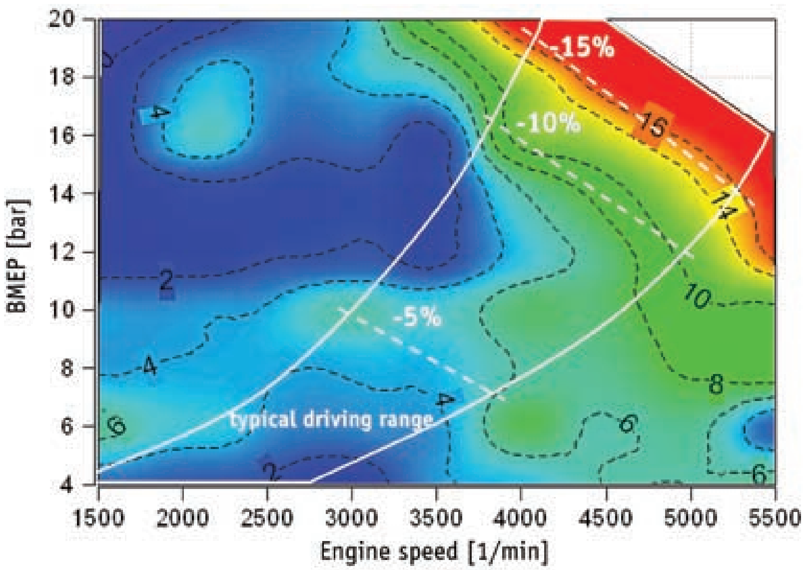

Figure 2: Map of fuel consumption reduction through the application of cooled EGR

The 32 mm deep air to air (direct) charge air cooling (CAC) in the demonstrator base vehicle was replaced by an indirect air to coolant cooler in a low temperature cooling circuit driven by a 50 W electrical coolant pump positioned in the left hand wheel bay. The low temperature cooling circuit used a full face 16 mm deep radiator. The indirect CAC was installed close to the engine and protected from air flow from the front end cooling pack. This compact installation resulted in short cooling lines and a small coolant volume. Although the conversion to indirect CAC resulted in 4.5 kg extra weight, the shorter charge air circuit had 7 litres less volume between the compressor and the throttle, which improved the transient response of the engine.

3 The Influence of EGR on the Combustion as well as Engine and Vehicle Operation

Modern gasoline engines have, through improved volumetric efficiency and combustion significantly improved efficiencies compared to earlier turbocharged engines. However, due to the limited maximum turbine inlet temperature, enrichment is needed at high engine speeds and load as well as with lower quality fuels. An effective means to reduce the need for enrichment is cooled EGR at higher engine loads.

The fuel saving potential of external EGR, in this case high pressure (short route) EGR was investigated on the test bed, **Figure 2**. The reference measurements for this investigation were the basis engine fuel consumption map when using internal EGR through the variable inlet and exhaust valve timing [2]. With the high pressure EGR the turbine entry temperature sank over most of the engine operation map; the limit of 950 C occurred only at higher speed and load conditions, which drastically reduced the enrichment requirement. The reduced component thermal loading (for exhaust valves, exhaust manifolds and turbocharger) and the improved ageing conditions for the catalyst mean that the emissions stability of the vehicle will be improved over a longer time or that a reduced catalyst precious metal loading can be used.

With cooled EGR increased heat will need to be rejected by the cooling system, **Figure 3**, since the higher engine heat rejection and higher EGR heat rejection occur under the same high engine load conditions. For continuous operation under higher ambient temperature conditions this additional heat rejection will be difficult to cool with existing vehicle cooling systems. However, for normal transient operation, where these conditions occur just for a short period of time, the cooling system will be sufficient.

4 Realisation of the Test Bed Results

To verify the test bed findings the high pressure EGR system was installed and calibrated in a demonstrator vehicle. In **Figure 4** the results from 6th gear full load accelerations measured on a chassis dynamometer with and without cooled EGR are shown. The top diagram shows the results without EGR: from a vehicle speed of about 170 km/h enrichment must be used to control the exhaust gas

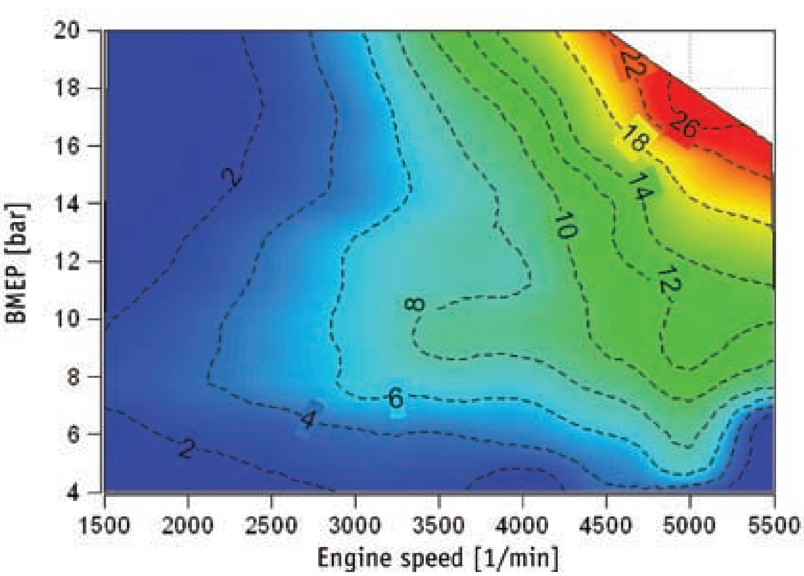

Figure 3: Heat rejection [kW] from the EGR cooler

temperatures. With high pressure EGR enrichment is not needed until a vehicle speed of about 220 km/h, since the exhaust gas temperatures are lower.

In order to check the real world fuel consumption, the demonstrator vehicle was tested on the „Black Forest Route“ (a drive from Stuttgart to Karlsruhe, along the Black Forest high road and then back to Stuttgart) with and without cooled EGR. The complete route is about 340 km long and includes town, country, motorway and mountain climb roads. With the weather and traffic conditions as close as possible the cooled EGR variant recorded a fuel consumption improvement of about 6 % compared to the baseline installation without cooled EGR.

5 Map-controlled Thermostat and Coolant Stand Still

For many years the thermostat, with its fixed opening temperature, has been the standard means of controlling the coolant temperature. However, this disregards the fact that for different engine operating conditions there are different optimal coolant temperatures. This load dependent operation of the thermostat can be achieved using the map controlled thermostat. The map controlled thermostat consists of a wax element that controls the coolant temperature under part load conditions. Through the use of heating via a resistive coil, the wax element can be heated up, representing a higher coolant temperature for the thermostat. Consequently, a higher coolant flow can be achieved through the thermostat to the radiator and the coolant temperature in the engine reduced, depending upon the installation by up to 30 K.

In order to confirm the effectiveness of the map controlled thermostat tests were undertaken on the engine running in stationary conditions. The coolant temperature (t_{mot}, measured at the engine outlet) was increased or reduced by 10 K from its basis of 90 C. In **Figure 5** effects of the changes in coolant temperature on the engine indicated mean effective pressure (P_{mi}), combustion timing centre (MFB_{50}) and fuel consumption (b_e) are shown.

In the part load region increasing the coolant temperature reduced the engine friction, hence the same brake mean effective pressure can be achieved with a lower indicated mean effective pressure. The reduced friction leads to reduced fuel consumption: reductions of up to 1.4% were measured without necessarily changing the combustion timing, which was already optimal at 8 degrees crank angle after top dead centre. At higher en-

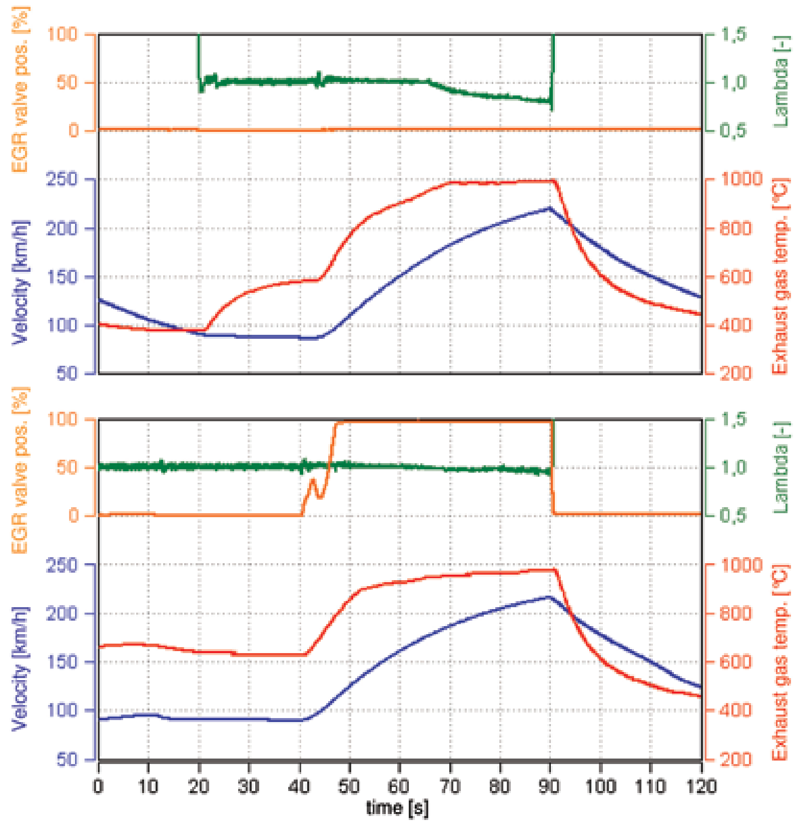

Figure 4: Vehicle acceleration in 6th gear, below with, and above without cooled EGR

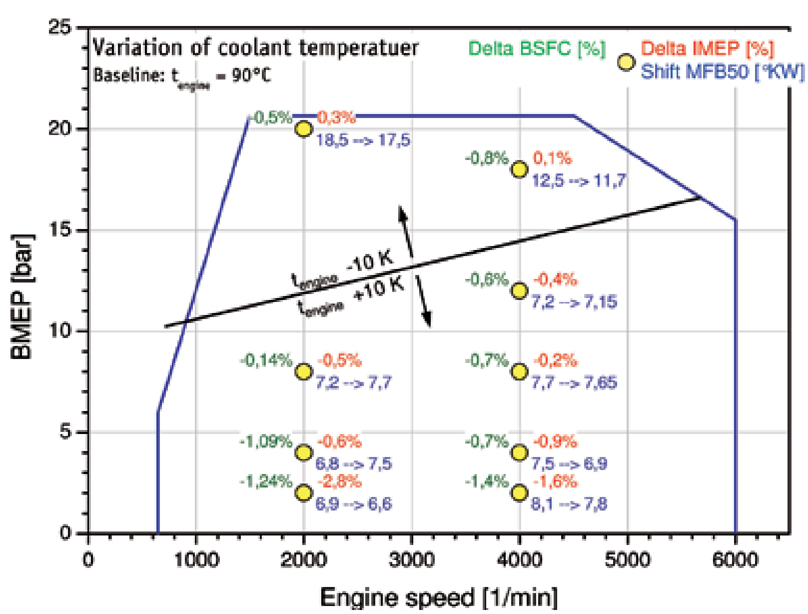

Figure 5: The effect of changes in the coolant temperature (tmot) on the combustion in the engine

gine loads and up to full load the coolant temperature was reduced. This increased the knock limit of the engine, allowing earlier combustion timing. The resulting efficiency improvement effect was greater than that due to any increased friction. In the measurements made, a 1 degree earlier combustion timing resulted in between 0.5 and 0.8 % fuel consumption improvement.

A further means to optimise the thermomanagement of the engine is to keep the coolant standing still during the engine warm-up. Since the frictional losses are higher with a cold engine, the engine coolant and oil should be brought to the correct operating temperature as quickly as possible. This is especially important in the cylinder head and the cylinder bores: the local temperatures climb quickly through the use of coolant stand still, reducing the friction and allowing improved combustion. In order to achieve the quicker temperature rise, the total thermal mass to be warmed up is reduced through the closing off of cooling sub-circuits, the reduction of the heat transfer to the coolant and the prevention of heat transfer from the engine through the use of coolant stand still.

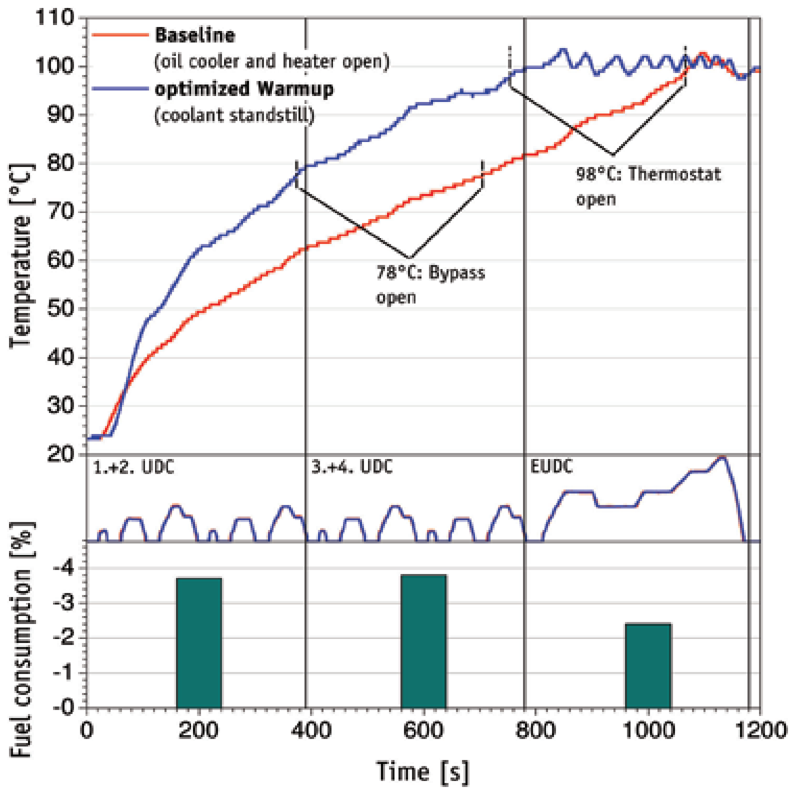

Figure 6: Reduction of the fuel consumption in the NEDC with the use of coolant stand still

Coolant stand still is achieved through the use of a throttle thermostat and on-off valves in the oil and cabin heating circuits. The throttle and map controlled thermostats are actually integrated in one component: both functions, the closing of the bypass circuits and the control of the coolant temperature, are possible with one wax element which acts on two plates and one sleeve in the thermostat housing. The information about the coolant temperature in the engine is transferred to the wax element via a small coolant flow. During the coolant stand still the mechanical water pump only needs a small flow in order to satisfy the cooling of the turbocharger and EGR cooler. The throttle thermostat opens at an engine outlet temperature of 78 C in order to prevent local boiling at the hottest engine components, for example at the exhaust valve bridge.

In **Figure 6** the variation of the coolant temperature and the fuel consumption reduction as a result of coolant stand still during the early part of the NEDC is shown, in comparison to measurements with an open coolant circuit. In both cases the map controlled thermostat with the integrated throttle thermostat and bypass was used. The coolant temperature was measured in the thermostat housing at the engine outlet. With conventional operation with open sub-circuits the bypass is normally opened after 700 s and the control temperature of 98 C is reached after 1,065 s. With coolant stand still the 78 C limit is reached after just 370 s and the 98 C limit after 755 s. The faster warm-up in the critical parts of the engine leads to a fuel consumption reduction over the NEDC of about 3 %.

6 Demand-orientated Control

The electrically heated wax element in the map controlled thermostat has a maximum power requirement of about 10 W. In the fuel consumption critical part load regions, where the engine temperature should be held at about 100 C, the thermostat controls without the need for electrical power. The desired temperatures are stored in a speed and load map, such as that shown schematically in **Figure 7**.

After long phases of engine idling, the engine cooling system is controlled to an exit temperature lower than the engine temperature in order to quickly reduce the engine temperature. Due to the placement of the map controlled thermostat at the engine exit there can be long delays in the response of the system, from between 20 to 40 s depending upon the operating point. There, apart from in transient operation, the heat transfer to and from the wax element is hard to control and, therefore, a time constant for the delay of the reference parameter is used. Placing of the map controlled thermostat at the engine inlet is recommended, since there the time constant for the system is smaller and better control would result.

The control of the indirect CAC in the low temperature coolant circuit follows an analogous strategy to that of the engine coolant: a PI controller from the BHTC library of controllers that allows the normal functionality, such as variable control parameter limits, stop and start of the integrator, and anti-windup (stopping the integrator when a parameter limit is reached). One part of

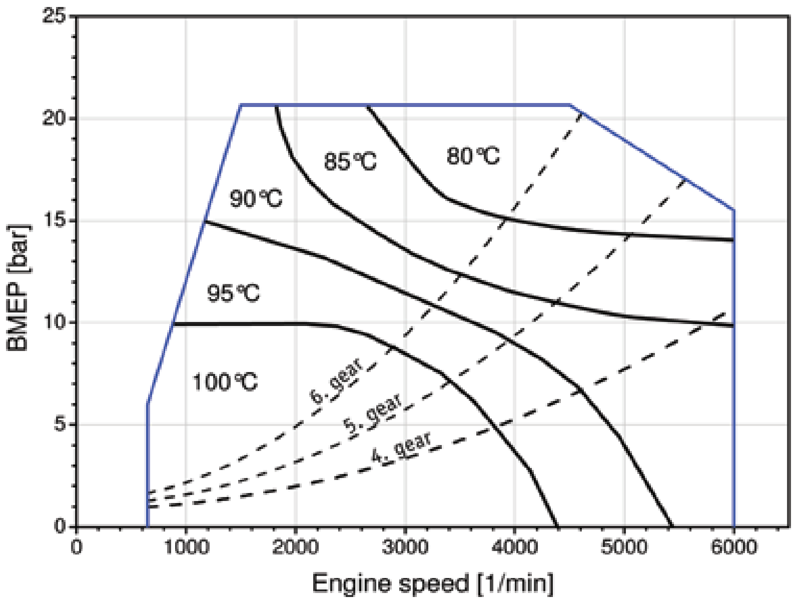

Figure 7: Coolant temperature limits across the engine map

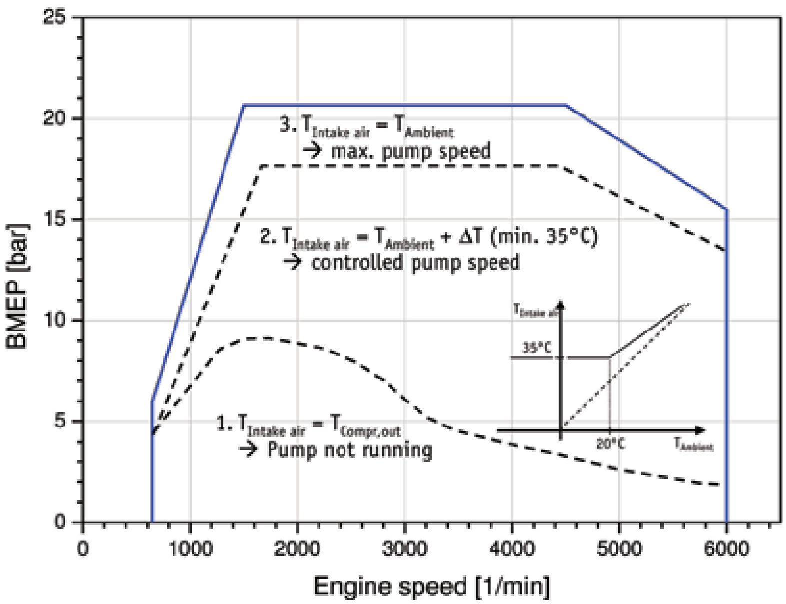

Figure 8: Charge air cooling control strategy regions across the engine map

the control is the 50 W speed controlled water pump: this offers advantages in the control of temperature peaks and energy usage compared to an on/off pump. The control parameter is the inlet air temperature after the CAC, which is controlled dependent upon the engine load, **Figure 8**. Below a defined engine power the cooling of the intake air is reduced by stopping the electric pump, since higher air temperatures at part load lead to effective de-throttling. Above this limit the pump runs in a controlled mode targeting a given charge air temperature, which is defined as a temperature above the ambient temperature. Above a given engine load condition, the pump runs with maximum speed and the maximum cooling performance is independent from the charge air temperature. The target charge air temperature is the ambient temperature. Operation of the electrical water pump at maximum speed during over run of the engine is a special condition: here the temperature in the low temperature cooling circuit will be reduced without considering engine fuel consumption. The control strategy described here was used during the Black Forest test runs: the electrical water pump was found to be in operation about 23 % of the time with ambient temperatures between 10 and 20 C.

The proportional control valve for the flow rate through the EGR cooler and turbocharger sub-circuit was set dependent upon the EGR rate and the engine load. On top of this was a two point control which, upon reaching a maximum temperature limit, completely opened the valve and, beneath a given temperature, allowed a minimum flow rate. Thus, in combination with the on/off valve for the cabin heater and engine oil cooler, the coolant stand still during engine warm-up could be realised with a mechanical water pump.

During the engine warm-up, which is critical for fuel economy, the number of electrical devices in operation on the vehicle was kept down. In this phase the operation of the electrical water pump for the low temperature cooling circuit for charge air cooling was prevented. Chassis dynamometer tests have shown that even with this strategy throughout the NEDC the inlet air temperature does not exceed temperatures which would mean engine efficiency reductions.

7 Conclusions

There are several possible technologies to reduce the CO_2 emissions of modern boosted gasoline engines. Of particular benefit are the use of external cooled exhaust gas recirculation and a reduction of the time for engine warm-up in the NEDC through the application of coolant stand still and a decoupling of unnecessary thermal mass. With the use of a map controlled thermostat, the coolant temperature can be tuned to the engine operating condition to further reduce the engine fuel consumption.

All of these technologies require an accurate calibration on the engine and in the vehicle, in order to reach the best results whilst considering the interactions and limits of the engine cooling both on the test cycle and in real world use. ■