Warm-Up Optimisation by means of Exhaust Heat Recovery

Knowledge Library

BorgWarner

Warm-Up Optimisation by means of Exhaust Heat Recovery

Driven by higher requests for engine efficiency, thermal management for combustion engines is receiving increasing attention. The engine efficiency potential is the result of improved combustion in the warm-up phase and a decrease in friction loss. BorgWarner evaluates the heating up behaviour of a modern vehicle in several testing cycles, including the Worldwide Harmonized Light-Duty Test Cycle (WLTC).

By Dr. Wolfgang Wenzel, Program Manager for PassCar Systems, BorgWarner,
Iago Gonzalez Tabares, R&D product Engineer, BorgWarner, and
Dr. Michael Becker, Director Advanced R&D, BorgWarner

Basic Conditions

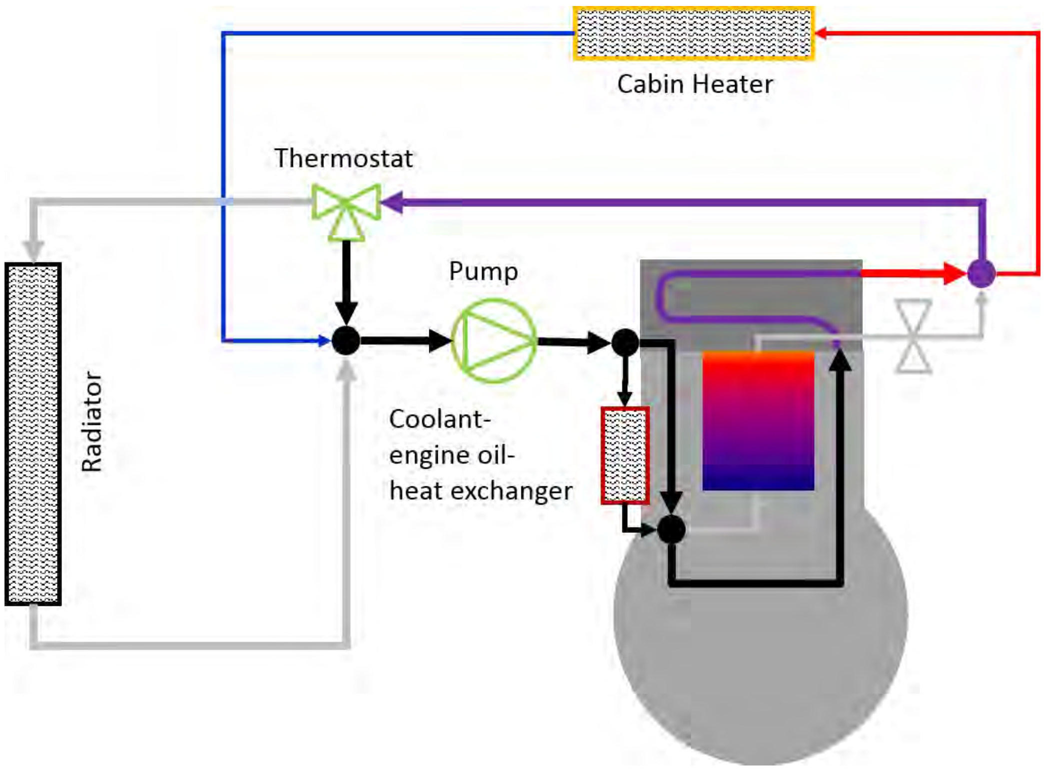
Due to the high efficiency of modern engines, the heat from the cooling system is limited in operating conditions with low engine load such as in the New European Driving Cycle (NEDC). For faster warm-up additional heat input may be used from other sources. Exhaust heat is favourable due to the high energy level. Two directions are possible: direct use of the exhaust heat via heat exchanger or indirect use of the exhaust heat with heat storage.

Basis Configuration

The selected vehicle is a VW Golf 1.2 TFSI with a seven-gear dual-clutch transmission. The vehicle is equipped with a turbocharged 1.2-l four-cylinder gasoline engine and stop/start system [1]. The temperature control for the engine cooling circuit is realised by a cooling module which consists of the mechanical coolant pump, the wax thermostat and an additional wax shut-off valve for the cylinder liner sub-circuit. In addition, the engine is equipped with an oil-to-coolant heat exchanger which also supports warm-up by transferring heat from the coolant to the engine oil.

Warm-Up Improvement

Considering fuel consumption, the main benefits from improved vehicle warm-up are reduced engine friction and cylinder wall heat losses. Different options for the reduction of fuel consumption in the warm-up phase are available. Warm-up of engine block and fluids is improved by stopping coolant flow in the complete engine or the engine block due to the fact that the piston group is responsible for the major part of the overall friction [2]. Ideally, this is realised by a separation of the cooling loop through the liner and the cylinder head, a so-called split-cooling layout. This more complex setup is chosen to allow to stop the flow in the liner while keeping the coolant flow through the cylinder head for protection from overheating.



Cooling system layout with the high-temperature circuit

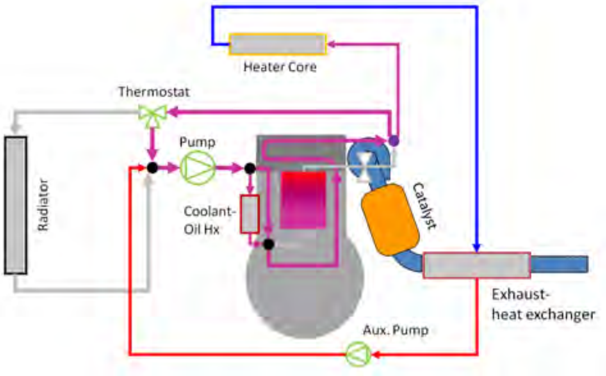
As previous investigations have shown, the reduction of auxiliary losses by adjusting the coolant flow to the actual demand helps to reduce fuel consumption. This can be realised by a variable electric or mechanical pump or the combination of both [3].

Another way to achieve an improvement is to use available heat from other heat sources, for example exhaust gas via exhaust gas recirculation (EGR) cooler or exhaust heat exchanger, and directing the heat to a target fluid to achieve maximal friction reduction. This can be coolant, but potentially also engine oil or rear axle oil.

Using stored heat from previous engine operation is another option. Different ways of heat storage are known, important criteria for vehicle application are high storage density and fast discharging capability. The simplest way is to store heated coolant in an isolated device but the benefits are limited. Another option is offered by phase change materials which can store a significantly higher amount of heat.

Exhaust Heat Recovery

Exhaust heat recovery (EHR) for engine warm-up is known since years [4]. Today only a few applications are on the market since the relatively low exhaust temperatures in the current test cycles, for example the urban part of the NEDC, lead to a limited fuel consumption be-



Integration of the exhaust heat exchanger in high-temperature cooling circuit

CYCLE	CYCLE CHARACTERISTICS										TEST DATA
	DURATION [s]	DISTANCE [m]	OVERALL STOP DURATION [s]	STOP DURATION – PERCENTAGE [%]	VEHICLE SPEED – MAX [km/h]	VEHICLE SPEED WITHOUT STOPS – AVERAGE [km/h]	VEHICLE SPEED WITH STOPS – AVERAGE [km/h]	ACCELERATION – MIN [m/s²]	ACCELERATION – MAX [m/s²]	ENVIRONMENT TEMPERATURE [°C]	FUEL CONSUMPTION [l/100 km]
NEDC	1180	11023	294	32.4	120	44.8	33.6	-2.1	1	20	5.43
WLTC	1800	23262	242	13.4	131.3	53.8	46.5	-1.5	1.6	20	5.63
FTP75	1874	17803	379	13.4	91.2	42.9	34.2	-1.5	1.5	20	5.55

Overview of the test cycles investigated

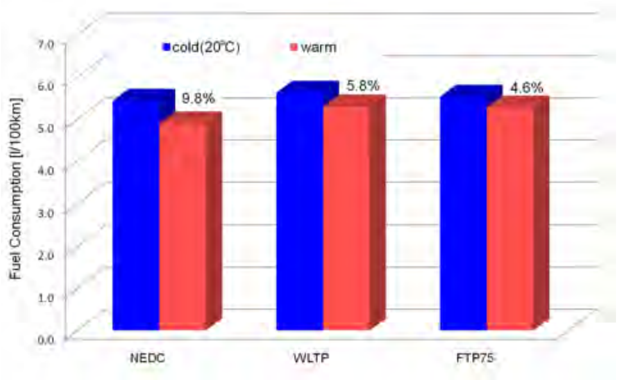
nefit for the OEMs. In general, EHR is possible with different heat sources: by a heat exchanger in the exhaust line or – if applied – in the EGR system. As mentioned above, the heat can be used in different ways: for engine, transmission or even for rear axle heating. The benefit versus cost ratio determines the layout chosen. It might be different for different applications. It is expected that the upcoming CO_2 legislation will be a driver for exhaust heat recovery systems.

The application of an exhaust heat exchanger is relatively straight forward. The heat exchanger can be easily derived from EGR cooler type heat exchangers. Only an additional bypass valve is required on the exhaust gas side to deactivate the heat exchanger when the engine is warm. The ideal location in the exhaust line is the position directly downstream of the catalyst, which also keeps the coolant hoses at a minimum length. To improve heat transfer into the engine oil, the exhaust heat exchanger is applied upstream of the oil-to-coolant heat exchanger in the heating sub-loop. A small auxiliary pump, which is fed by the board net, compensates the additional pressure drop and allows maintaining the flow during stop/start events.

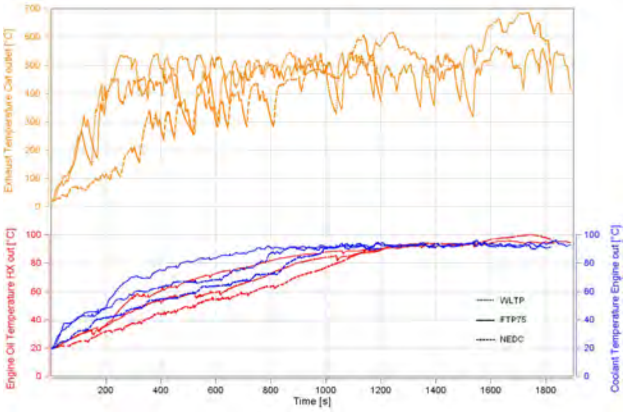
Vehicle Testing and Results

The vehicle evaluation was carried out by running different test cycles on a climatic test bench. To find the theoretically obtainable benefits test were run under standardised test conditions at 20 °C and also with the warm vehicle with all liquids at their operating temperature. After that a heat exchanger was applied to the vehicle as described above. However, due to packaging reasons the heat exchange had to be installed under the vehicle and higher benefits can be expected with a closer arrangement.

The monitoring of the engine state variables was realised by both external sensors and the communication with the vehicle CAN bus. An overall repeatability of +/- 0.5 % of the overall value for the cumulated fuel consumption was achieved. The base evaluation was carried out in three different cycles: NEDC, WLTC (Worldwide Harmonized Light-Duty Test Cycle) and the FTP75 (American Federal Test Procedure).



Fuel consumption for cold (20 °C) and warm start



Engine oil, coolant and exhaust gas temperatures for different cycles

Compared to the NEDC, FTP75 and WLTC are significant longer in duration and driving distance. Average speed and maximum acceleration are highest for the WLTC. Compared to the WLTC the FTP75 shows significantly higher engine load after 180 s which results in the shortest duration for engine warm-up.

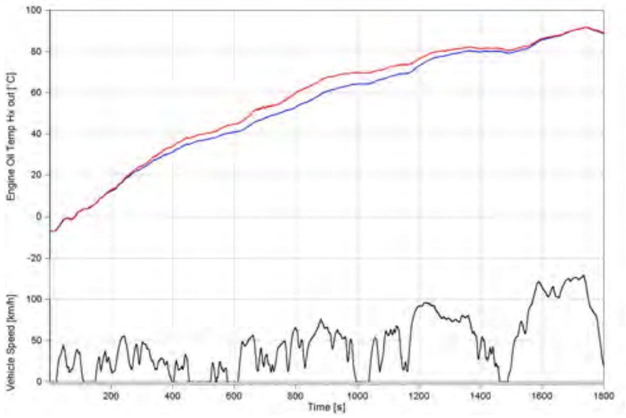
Base Evaluation

The maximum theoretical fuel efficiency potential for improved warm-up is given by the fuel consumption difference between a cold start at 20 °C and a warm start. The highest difference in fuel consumption was found for the NEDC with approximately 10 %. This is due to the slow warm-up and short duration of the cycle which results in a high importance of the warm-up phase for the overall fuel consumption. The exhaust gas temperature downstream of the catalyst as well as coolant and engine oil temperatures are plotted for the first 1000 s of the different test cycles (starting temperature at 20 °C). The coolant temperature was measured at the outlet of the engine, the oil temperature at the outlet of the oil-to-coolant heat exchanger. The NEDC shows the slowest coolant and oil temperature rise, the exhaust heat temperature also increases very slowly and reaches 200 °C only after approximately 5 min. So adding heat could bring the biggest fuel consumption benefit in the NEDC, but the available heat in the exhaust gas is also limited. In the WLTC an exhaust temperature of 400 °C is already reached after approximately 3 min and the warm-up is much faster. This is similarly true for the FTP75 cycle. So the WLTP and the FTP75 offer a lower theoretical potential of 5.8 and 4.6 % respectively. However, taking into account there is seem to be still potential for EHR.

Exhaust Heat Recovery

The testing with the heat exchanger in the exhaust was carried out at 20 °C and -7 °C. The -7 °C test temperature was chosen to show the potential of EHR for cold temperatures which are expected to be part of the upcoming WLTP (Worldwide Harmonized Light-Duty Test Procedure) legislation.

For the NEDC at 20 °C exhaust heat recovery did not lead to a significant increase of coolant and engine oil temperatures, thus no fuel consumption benefit was found – which is the reason why EHR has no significant volumes in the market today. For the FTP75 a small increase of the coolant temperature could be achieved. However, the temperature increase did not lead to a measurable fuel economy improve-



Engine oil temperatures with and without EHR system in the WLTC

ment. For the WLTC at 20 °C a fuel economy benefit of 1.2 % could be observed which was achieved by a more than 4 % improvement in the first phase (589 s) of the cycle. This improvement is due to the combination of the high relevance of this first phase for fuel consumption and the high amount of available energy to improve friction in that phase.

The tests at -7 °C were carried out for FTP75 and WLTC and fuel consumption benefits of 2.1 % for the WLTC and even 3.9 % for the FTP75 were found. The engine oil temperature in the WLTC could be increased by up to 7 K. Because engines run with very high friction at -7 °C, a faster warm-up phase leads to a significant friction benefit. That explains the large fuel consumption reduction for cold temperatures. The higher benefit of the FTP75 can be explained by the higher amount of available heat in the early phase which seems to be the dominating effect for the benefits found.

Summary and Conclusions

In this paper the analysis of advanced thermal management in a passenger car with a modern downsized engine has been presented. The warm-up behaviour for different test cycles including the upcoming WLTC was analysed and the potential of an exhaust recovery system for coolant heating with exhaust gas was investigated.

Even for a very fuel efficient powertrain with an advanced thermal management system clear potential could be shown with exhaust heat recovery, in particular for testing at low temperatures which the upcoming WLTP legislation will include. Especially with a close coupled EHR system featuring an exhaust gas to coolant heat exchanger – potentially combined with a LP-EGR system – a significant benefit can be expected which makes it a promising approach for future powertrains. In the next step a heat storage system will be applied to the test vehicle to investigate the benefits for the different test cycles.

References

[1] Szengel, R.; Middendorf, H.; Moeller, N.; Bennecke, H.: The new Modular Engine Platform from Volkswagen. In: MTZ 73 (2012), No. 6, pp. 26-32
[2] Beykirch, R. et al.: Das ganzheitliche FEV-Thermomanagementmodell für Antriebe von heute und morgen. MTZ Conference „Der Antrieb von Morgen“, Wolfsburg, 2013
[3] Wenzel, W.; Shutty, J.; Becker, M.: Advanced Thermal Management of Diesel Engines. In: MTZ 74 (2013), No. 5, pp. 38-42
[4] Diehl, P.; Haubner, F.; Klopstein, S.; Koch, F.: Exhaust Heat Recovery System for Modern Cars. SAE Paper 2001-01-1020, SAE World Congress, Detroit, 2001

Contact
Email: technology@borgwarner.com
For more information, please visit
borgwarner.com