Advanced Thermal Management of Diesel Engines

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The potential of thermal management with respect to CO2 reduction is given by faster warm-up of engine and drivetrain, reduced losses from water pump and fan and finally the operation of the engine in an optimal temperature range. In a new approach, BorgWarner applies a variable coolant pump and a fully controlled coolant valve to a conventional cooling system. Both components, as well as the viscous fan clutch, are controlled by a newly developed controls approach.

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Motivation

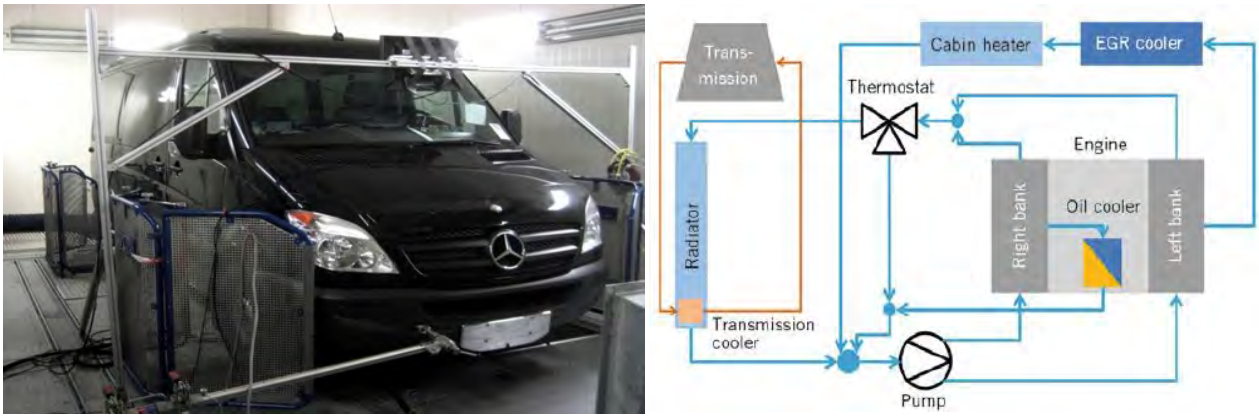
Driven by requests for higher engine efficiency, thermal management for combustion engine driven vehicles has received increased attention [1]. Standard coolant pumps which are linked to the engine speed provide too high flows of coolant in some driving conditions. Radiator flow control with wax thermostats is inflexible and relatively slow. Variable devices with a proper control can reduce engine warm up times and limit temperature fluctuations in transient conditions.

In a new approach, the combination of a dual mode coolant pump (DMCP) that can be driven by an integrated electric motor or the engine belt and a fully controlled coolant valve which replaces the wax thermostat, is applied to a conventional cooling system. The newly developed thermal controller activates both components in addition to the viscous fan clutch. To support the controller development a detailed simulation model of the complete test vehicle was created and accurately calibrated. The development was carried out via simultaneous simulation and testing. The performance was analysed in test cycles and the thermal management approach was refined iteratively.

Thermal System Setup

The selected vehicle is a Mercedes-Benz Sprinter model certified for sale in the U.S. The vehicle is equipped with a 3.0-l-six-cylinder Diesel engine (type OM642). The after-treatment system is designed to achieve US EPA/CARB 2010 emission limits. The series-production vehicle provides a conventional cooling system with wax thermostat.

The cooling system was modified, for example, with a DMCP. This pump was described in detail in the MTZ, [2], and is currently in series



Mercedes-Benz Sprinter in climatic test bench, OM642 cooling system

development. It replaced the mechanical coolant pump as a drop as a drop-in replacement and is connected to the accessory drive belt in the same manner as the stock coolant pump. The interface to the pump was realised via CAN to control both electrical pump speed and clutch position. The pump offers a high degree of freedom in operation: It can stop, run fully flexible in the range between minimum electric speed (due to sensor less control) and maximum speed which depends on electric motor size. The applied pump provides an electric range between 500 and 2500 rpm which is well suited for the coolant flow requirements in low- and mid-engine loads.

A prototype coolant control valve was used in place of the stock wax thermostat. The poppet style valve was combined with a brushed DC motor as an actuator. The valve could be controlled to any opening regardless of coolant temperature.

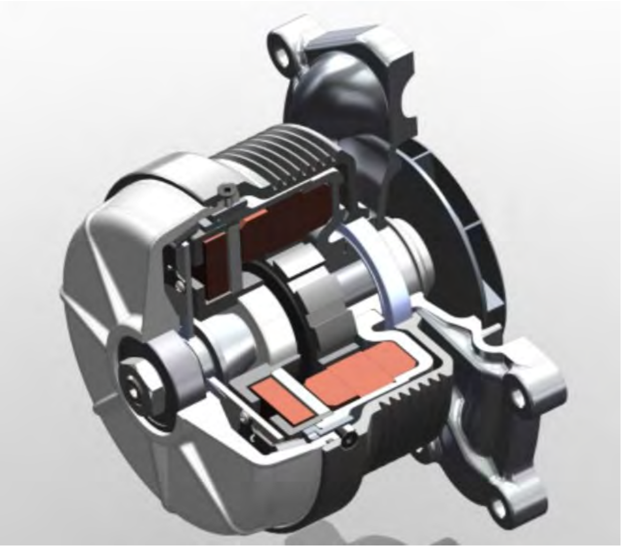
The engine driven fan with viscous clutch is part of the original equipment. The fan speed is adjusted to maintain optimal engine temperatures and to minimise parasitic losses. Due to the characteristics of the viscous clutch, it is spinning with a minimum speed when the engine is running. The top speed is limited by the pulley speed. For the majority of cycle testing, the fan remained at its minimum speed.

To optimally control these devices, the controller has to achieve three main goals: keep the engine in a temperature range that friction is minimized, protect the engine from overheating and create minimum auxiliary losses.

Simulation

A full vehicle simulation was created to support the development of the thermal management strategy [3]. The model was linked to a Simulink based controller to be able to use the same control software for both, the simulation and the vehicle testing. This reduced the development effort and improved the correlation between the model and the physical tests. The simulation was advantageous in different respects:

- The simulation with the calibrated model provides a repeatable platform which is able to evaluate small improvements and compare different configurations before experimental analysis is started.
- The simulation allows observing parameters that were not measureable on the vehicle (for example FMEP, heat transfer rates).
- It reduces development time and effort and thus cost.



Dual mode coolant pump (DMCP)

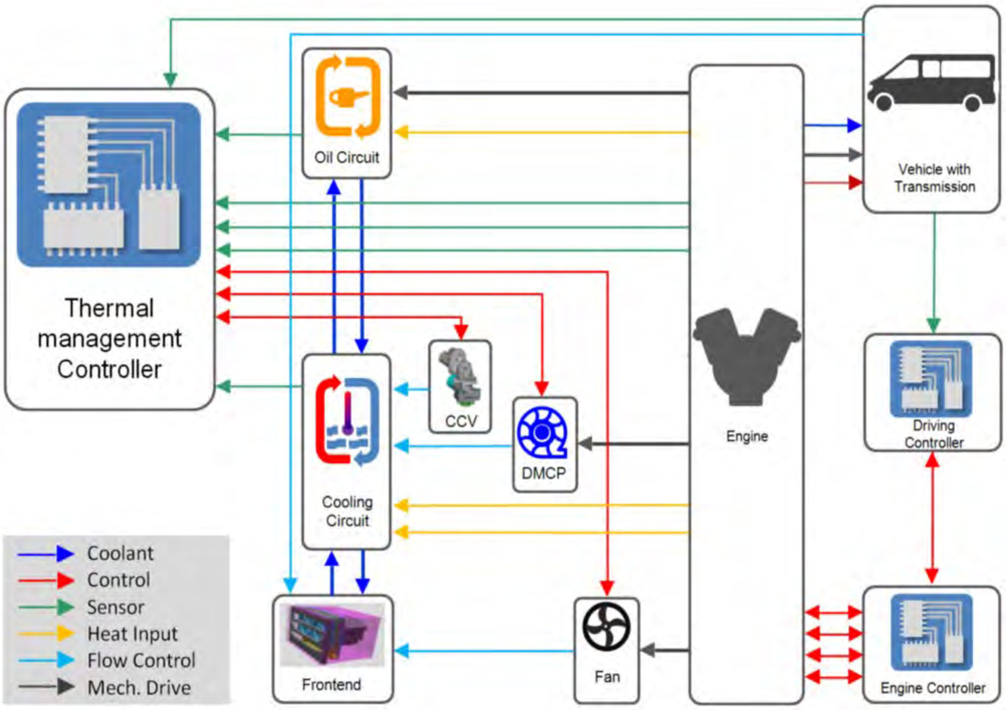
Model Structure

The host environment, in which the simulation ran, was Simulink with the model running as an S-function. Descriptions of the major elements of the simulation are given below.

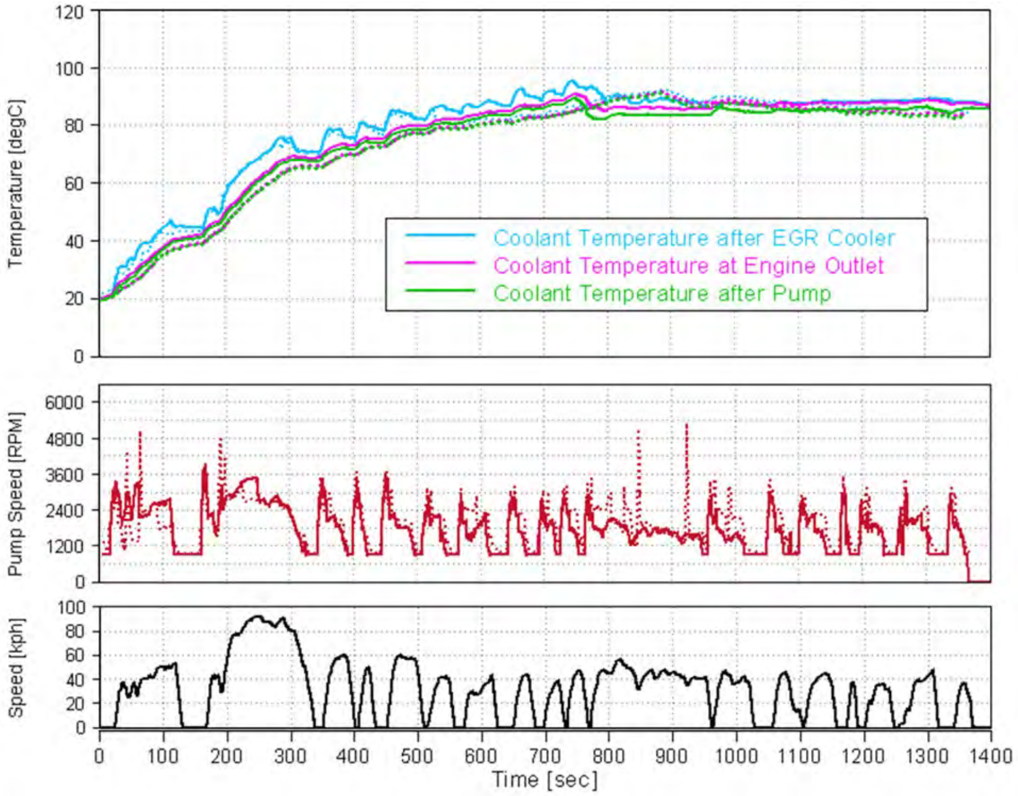
The vehicle sub model includes weight, rolling resistance, tire size, axle and gear ratio and aerodynamic drag. In addition, an algorithm which approximated the shifting strategy was developed; although for most cycles, a map of the actual time based shift points was used to improve repeatability. For the cycle simulation, a 1D front end sub model was derived from a rough 3D discretisation of the front end geometry to reduce simulation time.

The engine model was created based on engine parameters and calibrated with measured engine data. The 1D combustion model was converted to a mean value model using a neural network in order to significantly reduce the computing time. A comparison between the mean value model and the fuel combustion model showed very good correlation over the engine operating conditions studied. Engine fuelling, boost, EGR and bypass control were implemented in in the simulation model.

The cooling circuit was modelled in 1D with



Simulation block diagram



Simulation (dotted curves) vs. vehicle measurement (solid curves), comparison of coolant temperatures in FTP75 test

coolant pump, thermostat or controlled coolant valve and the fan with viscous clutch. Thermal inertia and heat transfers are modelled for the engine block, the transmission, rear axle housing and the complete exhaust line including the after-treatment system. Thermal efficiency effects were based on local temperatures such as block, cylinder wall oil temperature, crankshaft oil temperature, sump oil temperature, transmission oil temperature, axle temperature and coolant temperature.

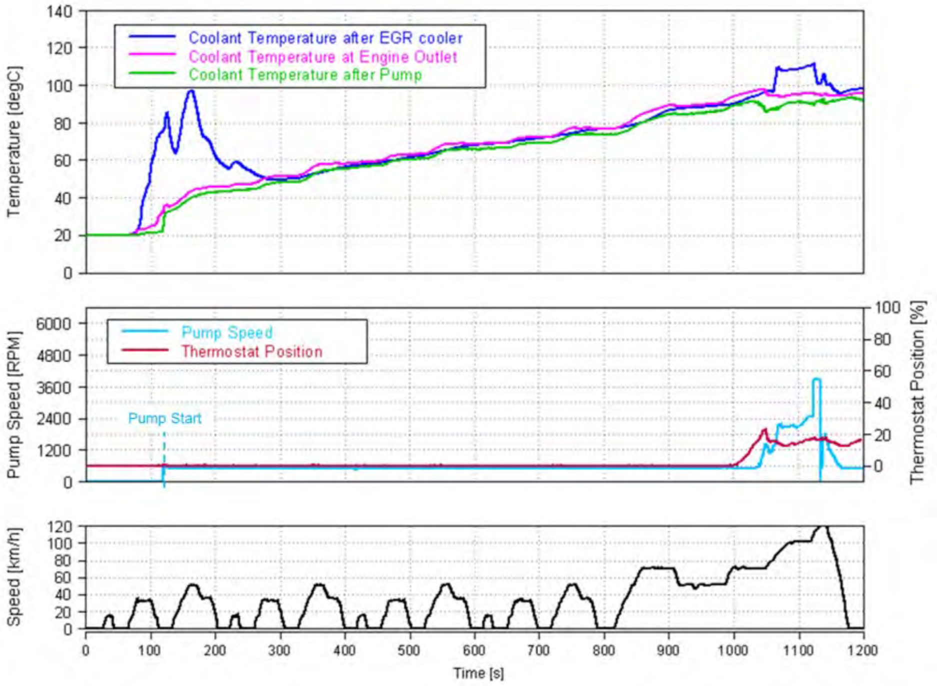
Model Validation

The model was compared to vehicle data at steady state conditions for correlation and during various drive cycles to insure a good transient performance match. For the matching shown below, the DMCP was operated in a clutched state so that it followed the engine speed with a fixed gear ratio (mechanical mode). The standard wax thermostat was used for the initial validation tests. The example given here shows key thermal parameters during a FTP cycle. The dashed lines represent the simulation results while the solid lines represent the vehicle testing data. Generally, the model is sufficiently accurate to use the simulation as a tool for controller development and optimization.

Thermal Controller

In order to run the simulation and vehicle through transient cycles, a model based thermal controller was developed. The controller was developed using Simulink and was used in both the PC based simulation environment as well as within a rapid prototyping ECU on the vehicle.

While preventing engine overheating is still a priority of the cooling system design, the project objective was more focused on how to

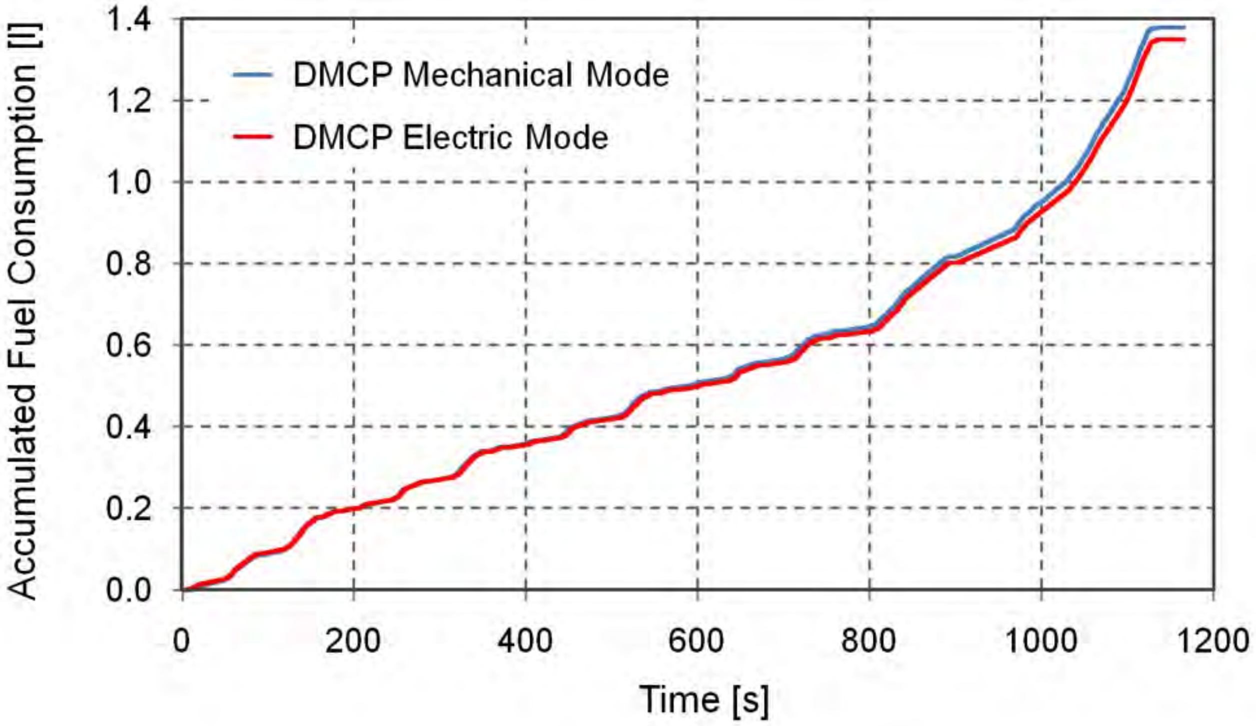


Performance of the thermal management controller, NEDC test results for coolant temperatures, pump speed and coolant valve position

achieve optimal temperatures with the minimum parasitic losses from the thermal system (that is pump power, fan power). In general, these two objectives could be achieved simultaneously; however, when in conflict, maintaining optimal temperatures had a much bigger effect on efficiency than reducing auxiliary losses. In addition to the above stated objectives, ensuring engine protection drove constraints on system operation. Due to the localised heat input in the engine and in other heat sources (for example EGR cooler), compromises had to be found to achieve both objectives. The system needs to heat up quickly but cannot tolerate local hot spots or large temperature gradients across components.

In the recent development work, the control of the DMCP speed and clutch state was of primary interest. Of further interest was the impact of adding a fully controllable thermostat (coolant control valve). Also the fan speed was actively controlled, but in practice, the controller strove to keep the fan at its minimum speed while controlling temperatures with the coolant pump and thermostat. A real-time capable model of the thermal system was also embedded in the controller. Values which would normally not be available to the controller in a production ECU were taken from the model and used for control.

Here, an example shows the controller performance in a NEDC cycle. The pump stop at the beginning for faster warm-up ends after 130 s to avoid overheating of cylinder head and EGR-cooler. The DMCP can be kept at the minimum speed until 1035 s after the start of the test. Only in the extra-urban part of the cycle, the pump speed is increased to maintain EGR cooler outlet temperatures; the controlled coolant valve had opened at 1000 s after test start. After 1125 s the pump switches to mechanical mode since this is the most efficient operating



DMCP: mechanical versus electric mode, fuel economy results in NEDC

mode at this point. The fan does not need to be switched on at all during the complete cycle. For more details and further results refer to [4].

Vehicle Testing

The thermal controller was implemented in a prototyping unit. The DMCP contained its own electric clutch and brushless motor controller. Commands for CCV position, pump speed and clutch state were handled via CAN interface. Power to drive the pump, fan and CCV were taken from the vehicle electrical system while power for DAQ and controller logic was taken from an auxiliary power source (to allow a good comparison). The vehicle was tested on a climatic test chamber and different test cycles were run (NEDC, US07, FTP75).

The fuel consumption benefit found in the NEDC was 2.1 % and is linked mainly to two different characteristics: zero or low flow in the engine leads to quicker local heating up, which reduces friction and improves combustion conditions. Secondly, the controlled pump speed leads to lower auxiliary losses. The controlled coolant valve does not provide a significant fuel consumption reduction in this setup. Its application only seems to make sense in conjunction with additional technologies for faster engine warm up.

Conclusions

A thermal management development approach and its application to a modern diesel powered vehicle have been presented. The vehicle was equipped with a DMCP, a variable coolant valve and an advanced controls approach. Thermal performance along with associated fuel economy improvements were shown for the NEDC test cycle. The DMCP offered significant fuel consumption benefits. The controlled coolant valve did not provide fuel consumption benefits in the investigated environment. However, the valve was an integral part of a more advanced concept investigated in the next project phase, where the cooling system layout was modified further and the vehicle was equipped with a heat exchanger for waste heat recovery.

References

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