

Active Thermal Management with a Dual Mode Coolant Pump

Varun Negandhi
BorgWarner Inc.

Dohoy Jung
University of Michigan-Dearborn

John Shutty
BorgWarner Inc.

ABSTRACT

A GT-suite commercial code was used to develop a fully integrated model of a light duty commercial vehicle with a V6 diesel engine, to study the use of a BorgWarner dual mode coolant pump (DMCP) in active thermal management of the vehicle. An Urban Dynamometer Driving Schedule (UDDS) was used to validate the simulation results with the experimental data. The conventional mechanical pump from the validated model was then replaced with the dual mode coolant pump. The control algorithm for the pump was based on controlling the coolant temperature with pump speed. Maximum electrical speed of the pump and the efficiency of the pump were used to determine whether the pump should run in mechanical or electrical mode. The model with the dual mode coolant pump was simulated for the UDDS cycle to demonstrate the effectiveness of control strategy. Benefits of using the dual mode coolant pump in reducing auxiliary power, reducing friction losses and increasing fuel economy of the vehicle was investigated in this study. Lastly, a hot start UDDS cycle was used to demonstrate changes in the operating mode of the pump. The results of this study confirm the capability of the DMCP in effective thermal management of the system with an increased fuel economy benefit of more than 2%.

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INTRODUCTION

In the past decade electrification of the various accessory components has increased in the vehicle due to the demand for higher fuel economy and stringent emission control. Thermal system of the vehicle is an example of such a case. Electrification in thermal management adds variability and efficient control over the system. Variable coolant pumps such as a basic on-off pump or a fully variable electric pump are already in production. Electric pumps have advantages such as variable speed, coolant flow after engine stop, and they support engine stop-start applications. However they also have disadvantages such as, the limitation of the electric power available to the pump in the usual 12/24 V automotive electrical system, poor efficiency at high pump loads and the failure of the electric motor, which can lead to severe engine heating problems. A DMCP therefore, can incorporate the advantages and overcome the shortcomings of a conventional mechanical pump and electric pump.

A DMCP is a concept part in serial development which features both mechanical and electrical drives. A solenoid and dry friction clutch controls the mode of the pump. In electric mode a solenoid is actuated and the dry friction clutch is opened against the clutch spring, which allows the electric motor to drive the pump shaft. In mechanical mode, the solenoid is turned off and the clutch is engaged, thus the pulley is connected to the pump shaft. Speed of the pump in mechanical mode is determined by engine speed and pump pulley ratio. The mechanical mode also acts as a fail safe mode. The scope of this study is to develop a control scheme for determining the speed of the pump and its desired mode of operation and investigate the effect of a DMCP on auxiliary losses, friction losses and fuel economy.

For several years there has been research on the control of electric pumps and electrification of thermal management systems. Cortona et al. [1] developed a model to represent thermal behavior of the engine and cooling circuit. The control for electric pump and valve was the focus of the

study. They showed the possibility of reduction in coolant pump energy needs and duration of cold-start phases. Allen et al [2] discussed the problem of mechanical cooling systems and provided a base for an ideal cooling system by using an electric pump and valve. Wagner et al. [3, 4] developed a lumped parameter thermal model and real time control algorithms to study the effects of an electric pump and valve on thermal management. Chalgren [5] investigates various cooling system flow circuits and their effects on heater performance and engine warm-up by using an electric pump and 2-way electric flow control valve. Cho et al [6] used a GT-cool model of a V6 diesel engine to investigate the use of an electric coolant pump in improving cooling performance and fuel economy. All previous studies have investigated the use of an electric pump in the thermal management system.

In this study a highly detailed one dimensional GT-Suite model was used to represent the cooling system, engine, vehicle, auxiliary components and engine controls of a light duty commercial vehicle with a V6 diesel engine. The represented base vehicle has a mechanical coolant pump, mechanical thermostat and viscous fan. The model was run with this conventional configuration for validation with experimental data and to provide a base for result comparison. The mechanical coolant pump was then replaced with a DMCP and a control algorithm was developed to demand the desired speed and operation mode of the pump. Next, the model was simulated to run various drive cycles and results were compared with the base run.

MODEL

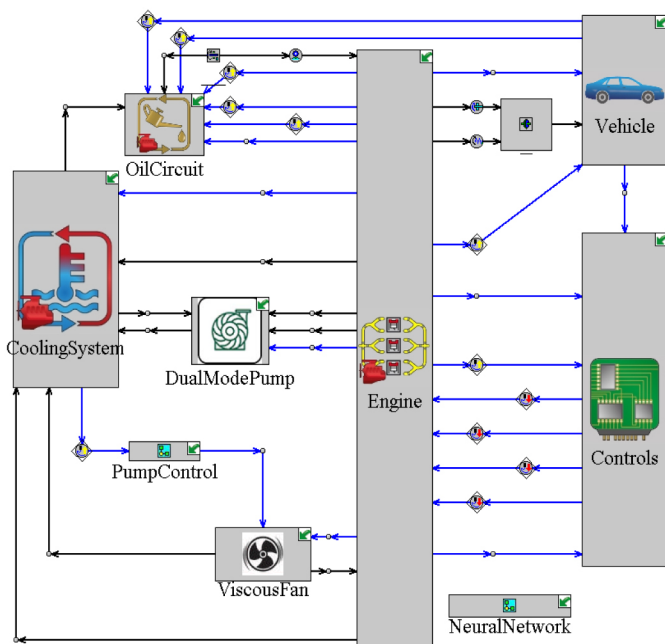


Figure 1. GT-suite 1D - Model Subassemblies

GT-suite is used to develop a one dimensional model for a V6 3.0 L diesel engine [7]. The model consists of the representation of the cooling system, engine, vehicle,

turbocharger system, high pressure EGR system, auxiliaries such as coolant pump, oil pump and fan, oil circuit and engine controls. A figure showing the different subassemblies of the model is shown in Figure 1. Below is a description of key subassemblies.

Engine

A mean value engine model is calibrated from a detailed engine model which was validated using measured data from the engine test bench. Since the scope of this study was to implement various control strategies, a detailed engine model would lead to high simulation times. The performance of this mean value engine is represented by the neural network which predicts the behavior of the engine based on six significant inputs namely; engine speed, intake pressure, intake temperature, back pressure, fuel flow rate and percentage of EGR. Neural network predicts volumetric efficiency, Indicated Mean Effective Pressure (IMEP), exhaust temperature, heat transfer to coolant and heat transfer to oil. The neural network is trained by steady state test data taken at various operating points. This subassembly also contains the intake and exhaust system which is modeled according to geometry. A Variable Turbine Geometry turbocharger is modeled in this subassembly.

Vehicle Model

The vehicle model is based on a light duty commercial vehicle. This subassembly establishes the transfer of the vehicle speed, grade and wind into engine speed and engine load. Therefore the vehicle weight, the frontal area and the drag loss has to be defined in the model as well as the tire rolling resistance and the inertias of the moving parts. The transmission elements require values for gear ratios and implementation of shift control strategy. An algorithm for the shifting strategy was calibrated based on the test results. The shift control strategy also takes into account the transmission efficiencies based on the temperature of the transmission fluid. Vehicle speed (drive cycle) is provided as a target to the model. To achieve the target speed a GT-suite target vehicle PID controller is used which controls the target speed based on accelerator pedal and brake pedal position.

Cooling System

The vehicle used for this study has an unconventional cooling system layout. The layout is shown in Figure 2. The coolant flows from the pump and splits into the left and right engine blocks. Most of the coolant from the block passes through the thermostat, however a small portion of the coolant out of the engine block flows through the oil cooler and EGR cooler where it gets heated up and it is mixed with the coolant out of the radiator or the bypass loop. This is the basis of the warm up strategy of this vehicle. Cold coolant is heated up in the engine and further heated up by the EGR cooler. Only a small flow is diverted to the coolers, such that there is a high temperature difference across the coolers.

MODEL VALIDATION

A light duty commercial vehicle currently in production with a V6 3.0 L diesel engine with the cooling system layout shown in Figure 2 was run on the vehicle dynamometer. The experimental data generated by this test was used to validate the GT-suite model. The drive cycle and input conditions were set according to EPA schedule for the UDDS drive cycle. Ram air speed was held as the vehicle speed for the bench test and simulation setup. The fan drive in the vehicle is a viscous clutch fan drive in which fluid viscosity is used to maintain the required gear ratio with the fan pulley to achieve the desired fan speed. However, even if the desired speed is zero there is a slip induced due to fluid friction, therefore there will be a minimum fan speed depending on the engine speed. This fan speed is measured and imposed in the simulation as the minimum speed of the fan.

Figure 3 shows the comparison of measured coolant temperature and simulated coolant temperature out of the engine and EGR cooler. It can be clearly seen that the model can predict the coolant heat up and cooling system performance during a transient cycle. Figure 4 shows the comparison between vehicle speed and engine speed. This shows that the simulation can achieve the target vehicle speed and translate the vehicle speed correctly into engine speed. The difference between the measured and simulated engine speeds is mainly due to the gear shifting strategy.

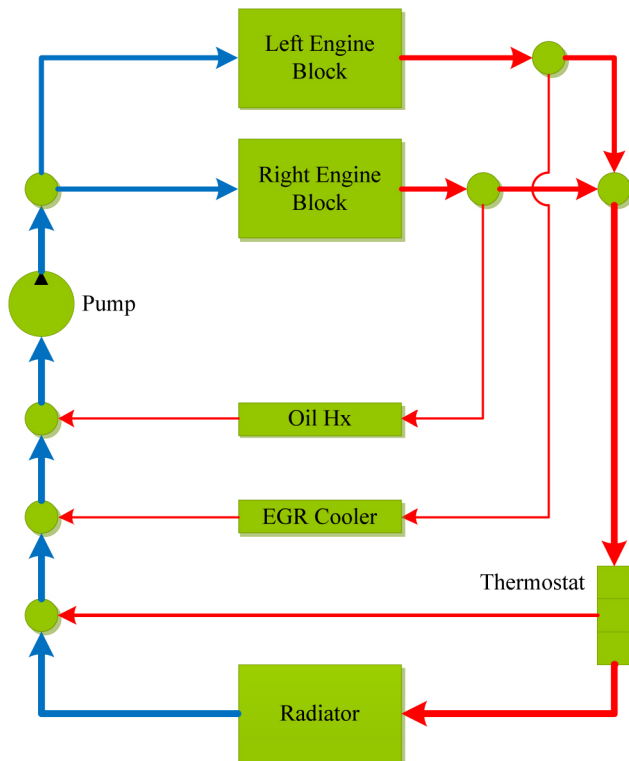


Figure 2. Cooling System Layout

According to the layout, a cooling circuit model is built up based on the geometry of the coolant ducts, the EGR coolers, the oil-coolant heat exchanger, the passenger compartment heater core, the thermostat, the coolant pump and the viscous fan. The engine block, piston mass and cylinder mass (cylinder liner and mass of engine block between the cooling jackets and piston) are modeled as thermal masses whose thermal energy is actuated by the neural network. The heat transfer and pressure loss data of the heat exchangers in the model which are radiator, oil cooler and EGR cooler are evaluated by experimental analysis on component test stands. In the base model the pump is modeled as a mechanical pump with a direct ratio to engine speed, the thermostat is a wax thermostat and the fan is a viscous fan. The flow and efficiency values of the fan and the pump were evaluated on a component test stand and directly used for the model elements. Thermostat lift table and flow areas were calibrated from experimental data.

Accessory loads on the engine are modeled as mechanical links in the GT-suite model. These mechanical links impose the power required to drive the pump as a power loss on the engine performance. Friction Mean Effective Pressure is calculated using a temperature versus engine speed based friction map. Temperatures used for the friction map are, metal temperature of block and piston, and oil temperature in the oil sump. Each of the temperatures is weighted according to their influence on the frictional losses.

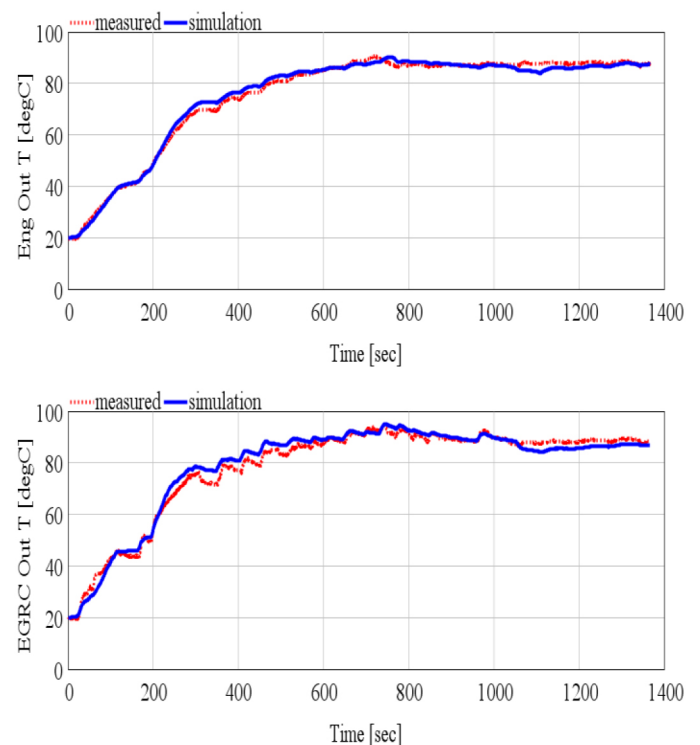


Figure 3. Comparison of Engine out temperature and EGR cooler out temperature