

Effect of Engine Oil Heater Using EGR on the Fuel Economy and NOx Emission of a Full Size Sedan during Cold Start

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ABSTRACT

In cold start driving cycles, high viscosity of the lubrication oil (engine oil) increases the mechanical friction losses compared with warmed up condition. Thus, an engine oil warm up system can provide the opportunity to reduce the mechanical friction losses during cold start. In this study, an engine oil heater using EGR is used for the fast warm up of the engine oil. This paper presents the effect of the engine oil heater on the fuel economy and emissions over a driving cycle (NEDC). A numerical model is developed to simulate the thermal response of the powertrain using multi-domain 1-D commercial powertrain simulation software (GT-Suite) and it is calibrated using test data from a full size sedan equipped with a 2.0L diesel engine. The model consists of an engine model, coolant circuit model, oil circuit model, engine cooling model, friction model, and ECU model. Also, a couple of the engine oil heater designs are compared using CFD to maximize the heat exchange rate and minimize the pressure drop across the oil heater. Selected engine oil heater design is modeled using Matlab-Simulink to integrate the engine oil heater model with the powertrain model developed using GT-Suite. The integrated model is used to compare the base system with the new system with engine oil heater based on the fuel economy and NOx emission.

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INTRODUCTION

Advanced thermal management of engine is one of the technical solutions to improve the fuel economy and reduce the CO₂ emission. Among the advanced thermal management systems, wasted heat recovery system can improve the fuel economy significantly because about 60% of energy is wasted into coolant and exhaust gas. One of the ways of wasted heat recovery is generating power from the wasted heat. But the system requires considerable additional components and change of the powertrain system architecture. Another way of wasted heat recovery is utilizing the wasted heat for fast warm up of the engine. Fast warm up can improve the fuel economy by reducing the friction losses during cold start. Thus, a number of researchers have been conducted the studies on new systems for fast warm up experimentally and numerically.

Will and Boretta studied a technique to warm up the engine oil to reduce friction losses. They found that fuel economy can be improved by 7% and CO emission can be reduced by 27% with the warm up technique over NEDC driving cycle at the ambient temperature of 22°C[1]. Burke et al. conducted experimental study on new warm up systems for fast warm-up of engine. They found up to 4% of fuel economy can be improved by using new fast warm up systems including a coolant throttle valve, variable flow oil pump (VFOP), and heat exchanger between exhaust gas and engine oil. But, it is also found that 3% of NOx emission is increased by the application of the

systems [2]. Lee et al. estimated the effect of a heat exchanger between exhaust gas and engine oil and an electric heater of Automatic Transmission Fluid (ATF) on the fuel economy. Based on the results of numerical simulation, they estimated the fuel economy improvement is 2.1% at 24°C and 7.2% at -7°C of starting temperature[3]. All of these previous studies showed that significant fuel economy improvement is possible only by fast warm up reducing friction losses. The results also show that the trade-off between the fuel economy improvement and emission (NOx) should be considered for the application of warm up system.

In this study, an engine oil heater using EGR is used for the fast warm up of the engine oil. This paper presents the effect of the engine oil heater on the fuel economy and NOx emission over a driving cycle (NEDC). A numerical model is developed to simulate the thermal response of the powertrain using multi-domain 1-D commercial powertrain simulation software (GT-Suite) and it is calibrated using test data from a full size sedan equipped with a 2.0L diesel engine. The model consists of an engine model, coolant circuit model, oil circuit model, engine cooling model, friction model, and ECU model. Also, a couple of the engine oil heater designs are compared using CFD to maximize the heat exchange rate and minimize the pressure drop across the oil heater. Selected engine oil heater design is modeled using Matlab-Simulink to integrate the engine oil heater model with the powertrain model developed using GT-Suite. The

integrated model is used to compare the base system with the new system with engine oil heater based on the fuel economy and NOx emission. Also, a control strategy of the oil heater is suggested considering the fuel economy and NOx emission.

SYSTEM MODELING AND VALIDATION

A Diesel engine model is developed using GT-Suite. The model consists of an engine model, coolant circuit model, oil circuit model, engine cooling model, friction model, and ECU model. Fig. 1 shows the overview of the integrated system model. The model can simulate both the thermal response of the engine and the fuel economy and emissions over a driving cycle. The model is developed based on the performance map data and thermo/fluid dynamics of the components. The engine modeled in this study is a 2.0 liter turbo charged Diesel engine.

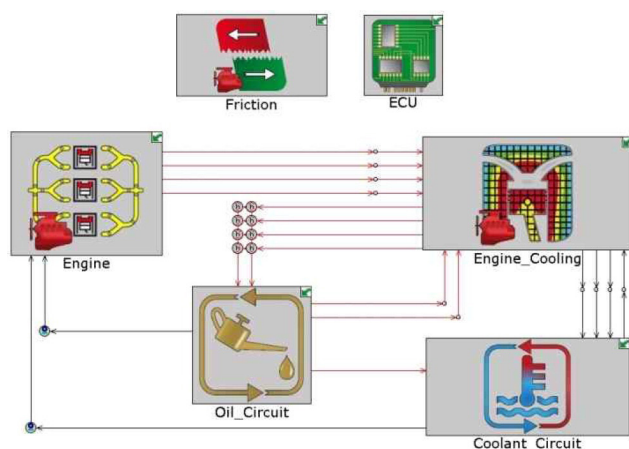


Figure 1. Overview of integrated engine system model in GT-Suite

Engine Model

Engine model calculates the BMEP, heat rejection, fuel consumption, and emission. Fig. 2 shows the snapshot of sub models of engine model. The engine model consists of Turbocharger, Charge Air Cooler (CAC), intake manifold, EGR cooler (gas side), cylinder, exhaust manifold and crank train.

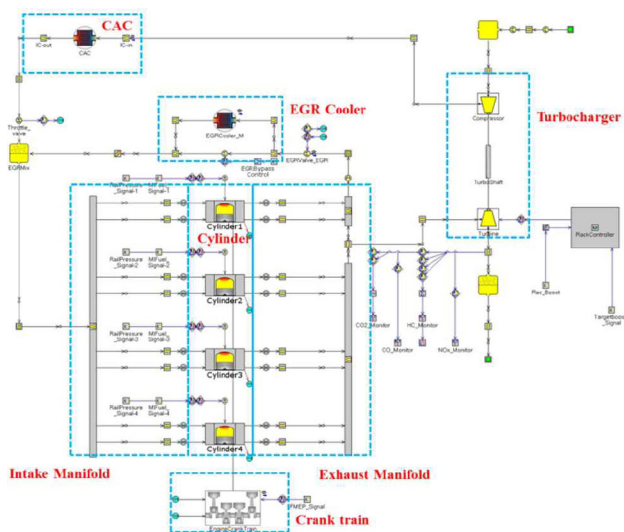


Figure 2. Overview of engine model in GT-Suite

For accurate estimation of engine performance, the speed of turbo charger, intake manifold gas temperature, intake manifold gas pressure, EGR fraction, mass flow rate of fuel, injection pressure, and exhaust gas temperature are validated with experimental results. DIPulse model is selected for the simulation of engine combustion. DIPulse model can predict the combustion rate and emissions of direct-injection diesel engine based on the multi-pulse injection. The entrainment rate, ignition delay, premixed combustion rate and diffusion combustion rate are the calibration factors which is calibrated with experimental data. The factors are calibrated based on the cylinder pressure, exhaust temperature, BMEP, and emissions. The after treatment systems are not modeled in this study. Thus, emission is measured at the exit of turbine.

ECU Model

In this study, the powertrain is modeled without vehicle model. Therefore, to simulate the response of the powertrain over a driving cycle (NEDC), the ECU controls the fuel flow rates to simulate the speed and torque profile which is supplied by the experiment of vehicle over the driving cycle. ECU controls injection timing, injection pressure, turbo charger boost, EGR and bypass.

Coolant Circuit Model

Fig. 3 shows the snapshot of coolant circuit model in GT-Suite. The coolant circuit model consists of a water pump, EGR Cooler (coolant side), oil cooler (coolant side), turbocharger (coolant side), cabin heater, radiator, radiator fan, and thermostat model. For the validation of cooling circuit model, the heat rejection from the oil cooler and radiator, the coolant flow rates at every part, and the coolant temperature are calibrated with experimental data.

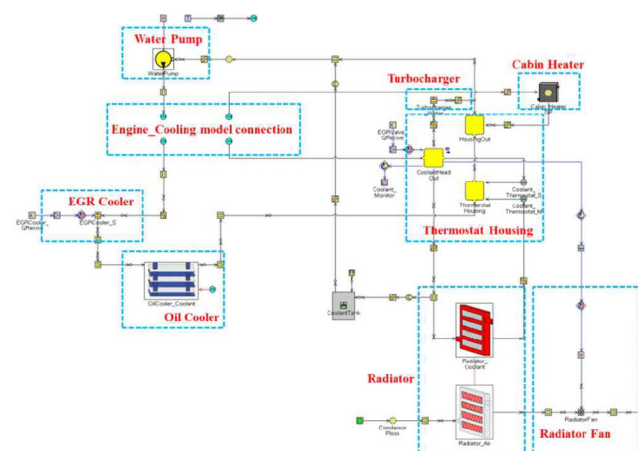


Figure 3. Overview of coolant circuit model in GT-Suite

Engine Cooling Model

Engine cooling model calculates the heat transferred to coolant and oil via cylinder liners, pistons, valve ports, valve guides, cylinder heads, and water jackets. The heat rejected to the cooling system is calculated by the combustion model. Fig. 4 shows the snapshot of engine cooling model in GT-Suite.

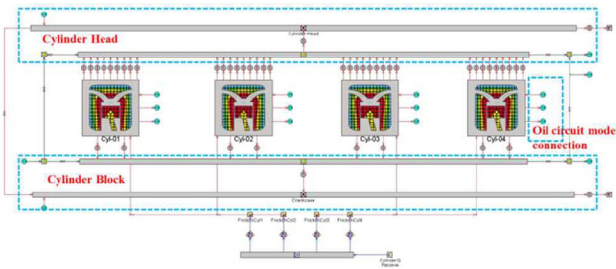


Figure 4. Overview of engine cooling model in GT-Suite

Friction Model

Friction model calculate FMEPs of moving parts including pistons, connecting rods, bearings, crank shaft, cam shaft, and pumps. Friction model is developed based on look up tables which are consists of engine speed, oil temperature, and FMEP. Fig. 5 shows the normalized FMEP of components depending on engine speed at 90°C. Experimental friction data at the oil temperatures of 60°C, 90°C, and 110°C are used for the generation of the FMEP look up table. For the simulation at low temperature, the look up table is extrapolated down to -20°C by using Eqn. (1) suggested by Shayler et al. who studied engine friction under cold and low speed conditions depending on oil viscosity [4] [5]. FMEP at different viscosity is calculated as

$$FM EP = FM EP_{ref} \left(\frac{\mu}{\mu_{ref}} \right)^n \quad (1)$$

where n is determined by experimental friction data. Fig. 6 shows the normalized total FMEP depending on oil temperature.

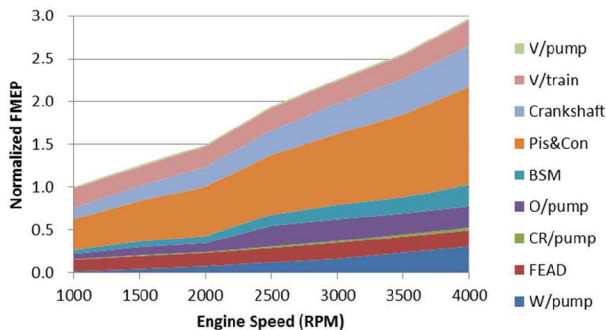


Figure 5. FMEP contributions of friction components at the oil temperature of 90°C depending on engine speed

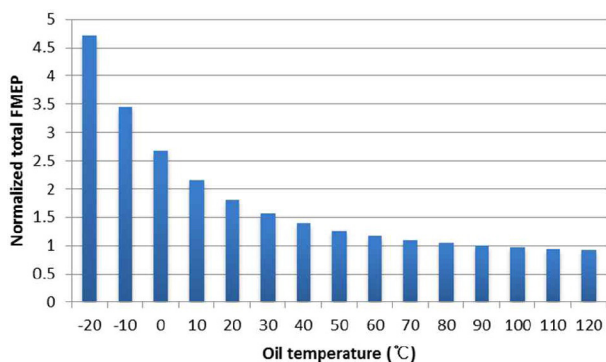


Figure 6. Total FMEP depending on oil temperature (normalized by the FMEP at 1000RPM)

Instant total FMEP is considered as a load on the crank train of the engine model. The FMEP of each moving part is considered as heat rejection in each moving part. The heat rejection rate in each moving part is calculated as

$$Heat Rate (W) = \frac{FM EP(kPa) \times V_d(m^3) \times N(RPS)}{2} \quad (2)$$

where V_d is the displacement volume and N is engine speed. Engine speed is used for the calculation of the heat rejection from pistons and main bearing, but a half of engine speed is used for the calculation of the heat rejection from valve train.

Oil Circuit Model

Oil circuit model consists of an oil pump, relief valve, oil thermostat, oil cooler (oil side), oil filter, turbocharger (oil side), main gallery, cam bearing, main bearing, connecting rod bearing, piston oil jet, and oil pan. The oil flow rate and pressure are calculated in the model.

Fig. 7 shows the snapshot of the oil circuit model in GT-Suite.

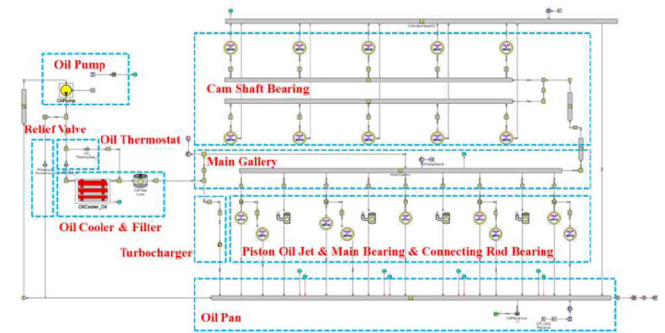


Figure 7. Overview of oil circuit model in GT-Suite

The engine oil temperature is sensitive to the mechanical friction. Thus, the validation of engine oil temperature depending on the operating condition is critical for the accuracy of the model. For the validation of engine oil temperature, the heat rejection from oil cooler, oil flow rate at thermostat, heat additions of cam bearings, main bearings and connecting rod bearings are calibrated with experimental data.

Oil Heater Design and Modeling Approach

Oil heater is the main component which warm up the engine oil during cold start by using high temperature EGR. To maximize the heat transfer rate and minimize the pressure drop across the oil heater, a couple of oil heater designs are compared by using CFD. Since the oil heater should be accommodated within a predetermined space, the size of casing is fixed. Then, the diameter and number of EGR tubes are changed to optimize the design. Among 6 designs of oil heaters listed in Table 1, 3 designs (Case 4, 5, and 6) as shown in Fig. 8 are modeled by using CFD. The simulation results are summarized in Table 2. Case 5 is selected as the optimal oil heater for the fast warm up system because it have minimal oil pressure drop with comparable EGR pressure drop and heat transfer effectiveness. The design is further changed to reduce the pressure drop in oil channel. The channel and casing length is changed from 130mm to 180mm resulting in lower pressure drop in oil channel of 0.32bar and higher heat transfer