MODELLING AND OPTIMAL CONTROL OF ENERGY-SAVING-ORIENTED AUTOMOTIVE ENGINE THERMAL MANAGEMENT SYSTEM

by

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The thesis simulates the engine's installation and uses conditions in the whole vehicle, such as the water tank, fan, the engine's arrangement in the engine room, accessories and pipe-line connections, etc. to build a test bench for the engine thermal management system. According to the thermal management simulation analysis software KULI modelling, the article designs the bench test conditions according to the parameter input requirements of the thermal management simulation analysis software. The accuracy of the model is verified by comparing simulation and test data, and the NEDC driving cycle is used to simulate the performance of the vehicle cooling system to guide the selection and matching of thermal management system components.

Key words: *test bench, engine, thermal management, numerical simulation*

Introduction

The heat generated by engine combustion is mainly transferred through three channels. The 40% of the energy is converted into useful work, 30% of the energy is taken away by the exhaust system, and the remaining 30% of the heat is transferred to the cooling system. In the era of energy conservation and environmental protection, waste heat recovery can convert low grade energy into high grade energy such as mechanical energy and electric energy or use this heat as a heat source in other fields to improve energy utilization efficiency. Complete attention from the industry. Especially in internal combustion engines, there are many technical solutions, such as turbo compound technology, organic Rankine cycle technology, waste heat refrigeration cycle technology, thermoelectric power generation technology*, etc.* The current research mainly focuses on the utilization of exhaust heat. The utilization of waste heat in the cooling system is still under study, and the coolant occupies most of the heat in the cooling system, so it is necessary to study the coolant's heat exchange.

To explore the engine's potential in utilizing the coolant waste heat, we need to study the coolant from the perspective of thermal engine management. From the perspective of the overall system, thermal engine management integrates the heat transfer of engine combustion, supercharging, intake and exhaust, cooling system, and engine compartment, thereby improving cycle efficiency and reducing thermal load so that the engine has an adequate cooling ca-

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pacity while maintaining a better cooling capacity. Good power and economy [1]. The cooling system is at the core of the thermal management system. If the cooling is insufficient, it will harm the metal and lubricating oil in the engine combustion chamber, reducing the strength and lubrication effect. If excessive cooling, it will affect the combustion and reduce the engine. Adequate power increases the fuel consumption per unit power, and the pollutants emitted will also increase. Besides, the temperature difference between the coolant's inlet and outlet should not be too large to avoid excessive local boiling. Under different loads and speeds, the engine's overall cooling demand will change accordingly, and the heat exchange amount of the coolant will also be different. In this study, a thermal management system bench test was carried out for a particular type of engine, using the obtained test data, modelling in the simulation software KULI, and using the simulation model to simulate the vehicle cooling system under the NEDC cycle.

Bench test of engine thermal management system

Bench structure

The engine thermal management system test platform is established based on the existing engine test bench. The test platform fully considers the vehicle's thermal components, including the cab heater, throttle heating device, and cooling pipe-line connection. The structure is the same as that of the vehicle. We installed a body engine cover on the test bench to simulate the cooling system's use environment in the engine compartment. Simultaneously, a simulated wind is set in front of the engine hood to simulate the air side's influence during vehicle driving. Set temperature, pressure, and flow measurement points on the cooling system [2]. The engine thermal management system test bench is shown in fig. 1.

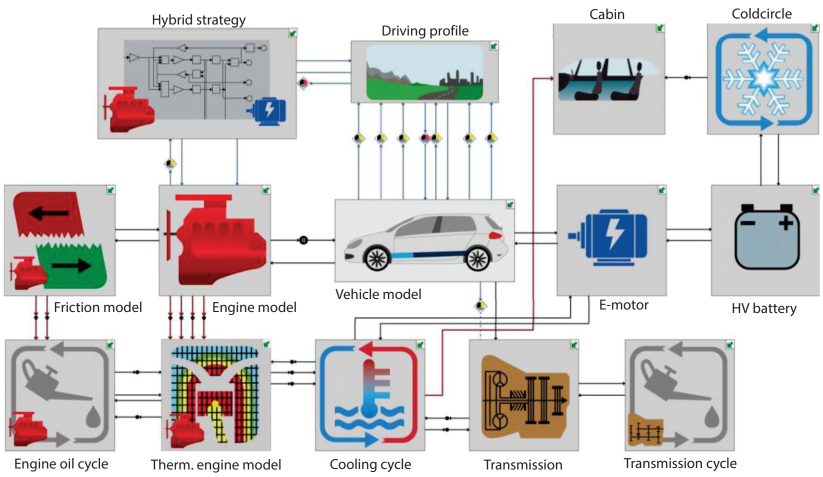

Figure 1. Engine thermal management system bench structure

Thermocouple lay-out

The Thermocouple is made according to the thermoelectric effect. Compared with other temperature measuring instruments, it has the following advantages: wide temperature measurement range and higher accuracy. It can realize long-distance multi-point detection, which is convenient for centralized control, digital display, and automatic recording and it can be made into a small thermocouple of size, small thermal inertia, suitable for fast dynamic measurement, point temperature measurement and surface temperature measurement. Because this test requires higher accuracy, multi-point measurement, and point temperature measurement of surface temperature, a thermocouple is selected as the temperature sensor [3].

The thesis uses copper and constantan metal wires with a diameter of 0.2 mm for welding, sets in a shrinkable heat tube, and uses a heat gun for further processing to produce a *T*-type thermocouple. The number and the temperature measurement grid lay-out are marked for easy calibration. Work progress, the paper arranges the thermocouples according to the distribution points determined in fig. 2. The specific arrangement method is to sew the thermocouples on the radiator's fins with wires to keep the position of the thermocouple measuring points relatively stable. Extend the thermocouple into the tube, clamp it with a clamp, connect the other end of the thermocouple to the NI9213 board, and connect it to the computer.

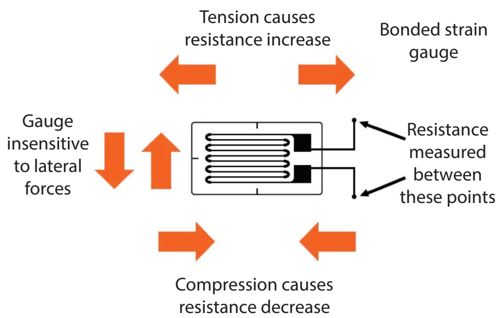

Figure 2. The 3-D lay-out of the temperature measurement network

Bench test

Through the steady-state and transient conditions of the engine, it measures the temperature of the engine's inlet and outlet water, the coolant flow rate and the pressure drop of the pipe-line system, *etc.*, which provides sufficient test data for software simulation modelling. It can also verify the accuracy of the simulation calculation. The main parameters of the engine are shown in tab. 1.

Table 1. Main parameters of the engine

Displacement, [L]	1.3996
Number of cylinders	4
Idle speed, [rpm]	650
Calibration speed, [rpm]	6500
Fuel grade	RON97
Engine oil viscosity grade	5W30

Steady-state test

When the engine outlet water temperature meets, the engine is considered to be in thermal equilibrium. Measure 25 steady-state operating points at 10%, 25%, 50%, 75%, and 100% of the speed and average significant pressure, respectively, to ensure the data's accuracy. The data we measured through steady-state operating conditions: engine fuel consumption, using the fuel consumption-line method to obtain the engine's mechanical loss; coolant and lubricating oil import and export temperature, flow, and other heat balance data; the heat dissipation area of the engine and the oil pan. And heat dissipation coefficient; environmental conditions (temperature, air velocity, *etc.*). At the same time, the thesis obtains the engine's heat release to the coolant by measuring the coolant's temperature and flow at the inlet and outlet of the engine during steady-state operating conditions, fig. 3.

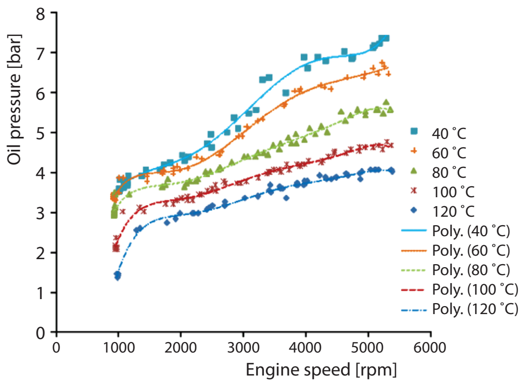

Figure 3. Heat taken away by engine coolant

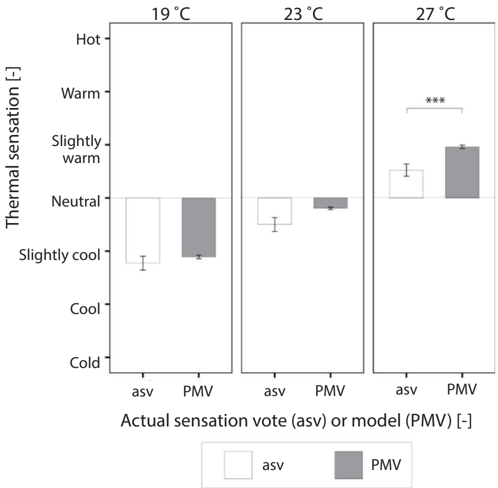

Figure 4. Step condition

Transient conditions test

To establish the transient simulation model of the engine in KULI, we need to measure the engine's thermal balance data under step operating conditions, as shown in fig. 4.

In the step condition test, the step load should cause noticeable heat flow changes, and the temperature change should not be too drastic, and the environmental conditions should not be changed. When measuring the thermal balance data before and after the step operating conditions, the engine should be steady. The engine's load remains constant, and the flow rate remains the same (*i.e.*, ignoring the thermostat). The measured data include engine speed, environmental conditions (temperature, air-flow rate*, etc.*), engine coolant inlet temperature and coolant outlet temperature, coolant flow rate, lubricating oil inlet temperature, and outlet temperature, lubricating oil flow rate, start time of step operating conditions and time when the engine reaches thermal equilibrium [4].

Establishment and adjustment of the simulation model

The heat input of the KULI model of the thermal management system is defined by the thermal map. The speed and load determine the engine's heat dissipation, including the heat transferred to the coolant and the oil and the heat generated by the friction of related parts. The calorific value is obtained through the engine thermal management bench test. To simulate the engine's transient process starting and warming up, we simplified the structure of the engine components in the KULI simulation model. The engine and other related masses are expressed by the lumped parameter method's point mass, which will be compared with the engine coolant and lubricating oil [5]. The mass that directly exchanges heat with the heat generated by friction is defined as direct mass, and other masses are defined as indirect mass. Figure 5 shows the four-mass model of KULI engine transient simulation.

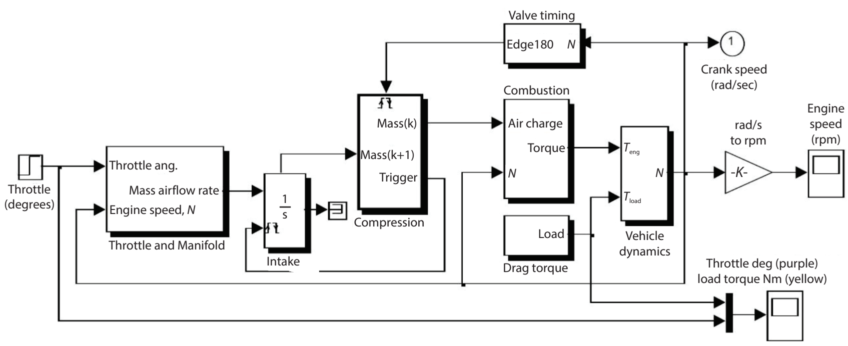

Figure 5. Four-mass engine model

The quality of direct heating by coolant circulation

The direct heating quality of cooling liquid circulation is defined by eq. (1), where $Q_{\mathrm{dir}w}$ is the direct mass heat of the coolant cycle, $m_{\mathrm{dir}w}$ – the direct mass of the coolant cycle, c_{pw} – the direct mass specific heat capacity of the coolant cycle, $\mathrm{d}T_w$ – the direct mass temperature difference of the coolant cycle, and a_{w} – the proportion of fuel heat flowing into the coolant cycle. The Q_{Br} is the heat generated by the fuel, b_w – the proportion of frictional heat flowing into the coolant circulation, Q_{rww} – the heat generated by friction, Q_w –the heat flowing into the coolant, $Q_{\mathrm{o}w}$ – the heat flowing from the lubricating oil into the coolant circulation, $Q_{\mathrm{ind}w}$ – the indirect flow the heat of the heating mass, and Q_{comp} – the heat flowing into the engine compartment from the surface of the engine:

$$Q_{\mathrm{dir}w} = m_{\mathrm{dir}w} c_{pw} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = a_w Q_{\mathrm{Br}} + b_w Q_{rww} - Q_w + Q_{\mathrm{o}w} - Q_{\mathrm{ind}w} - Q_{\mathrm{comp}} \tag{1}$$

The quality of direct heating of lubricating oil circulation

The quality of direct heating of lubricating oil circulation is defined by eq. (2), where Q_{diro} is the direct mass heat of the lubricating oil cycle, m_{dirw} – the direct mass of the lubricating oil cycle, $C_{p\mathrm{o}}$ – the direct mass-specific heat of the lubricating oil cycle, Q_w – the direct mass temperature difference of the lubricating oil cycle, and a_{o} – the proportion of fuel heat flowing into the lubricating oil cycle. The Q_{Br} – the heat generated by the fuel, b_{o} – the proportion of frictional heat flowing into the lubricating oil cycle, Q_{rww} – the heat generated by friction, Q_{o} – the heat flowing into the lubricating oil, $Q_{\mathrm{o}w}$– the heat flowing from the lubricating oil into the coolant cycle, Q_{indo} – the lubrication indirect mass heat of oil circulation, and Q_{pan} – the heat flowing from the oil pan into the engine compartment:

$$Q_{\mathrm{diro}} = m_{\mathrm{diro}} c_{\mathrm{po}} \frac{\mathrm{d}T_o}{\mathrm{d}t} = a_{\mathrm{o}} Q_{\mathrm{Br}} + (1 - b_o) Q_{rww} - Q_{\mathrm{o}} + Q_{\mathrm{o}w} - Q_{\mathrm{indo}} - Q_{\mathrm{pan}} \tag{2}$$

Indirect quality

The indirect mass is defined by eq. (3), where Q_{ind} is the indirect mass heat, m_{ind} – represents the indirect mass, k – the thermal conductivity, A – the heat transfer area, T_{dir} – represents the direct heating mass temperature, and T_{ind} – the indirect mass temperature [6]:

$$Q_{\mathrm{ind}} = m_{\mathrm{ind}} c_p \frac{\mathrm{d}T}{\mathrm{d}t} = kA(T_{\mathrm{dir}} - T_{\mathrm{ind}}) \tag{3}$$

Heat transfer between lubricating oil and coolant

The definition of heat transfer between lubricating oil and cooling liquid is shown in eq. (4), where $Q_{\mathrm{o}w}$ is the heat from the lubricating oil to the cooling liquid, $k_{\mathrm{o}w}$ – the heat transfer coefficient between the lubricating oil and the cooling liquid, and $A_{\mathrm{o}w}$ – the lubricating oil and the cooling liquid. The heat exchange area T_{o} represents the lubricating oil temperature and T_w – the coolant temperature:

$$Q_{\mathrm{o}w} = k_{\mathrm{o}w} A_{\mathrm{o}w} (T_{\mathrm{o}} - T_w) \tag{4}$$

Heat transfer between engine surface and oil pan

The heat transfer between the engine surface and the oil pan is defined by eq. (5), where Q_{con} is the convective heat, k_{con} – the convective heat transfer coefficient, A_{sur} – the engine surface area, T_{sur} – the engine surface temperature, and T_{comp} – the engine compartment temperature:

$$Q_{\text{con}} = k_{\text{con}} A_{\text{sur}} (T_{\text{sur}} - T_{\text{comp}}) \tag{5}$$

The convective thermal conductivity k_{con} in eq. (5) is determined by the air-flow rate obtained by the bench test measurement. According to the different air-flow rate, different formulas are used in the model to calculate:

$$v \leq 5m/s : k_{\text{con}} = 5.8 + 4v + c_{\text{o}} \tag{6}$$

$$v \leq 5m/s : k_{\text{con}} = 7.14^{0.78} + c_{\text{o}} \tag{7}$$

where the constant c is used to modify the theoretical equation. The lubrication system and the cooling system have heat exchange in transient conditions, so they need to be studied separately. Due to the complexity of parts geometry and heat flow, the heat transfer area and heat transfer coefficient are usually set based on empirical values. The heat exchange between the engine surface and the air is also considered in the model [7]. Through this model, we can analyze the non-steady interaction between the heat transferred from the engine to the coolant and the radiator's heat dissipation.

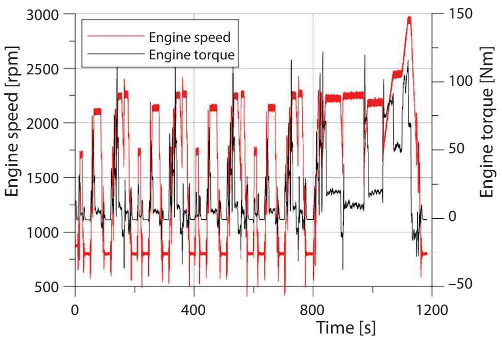

Figure 6. Temperature changes of coolant and lubricating oil under NEDC operating conditions

Analysis of simulation results

The NEDC cycle condition is used as the driving cycle simulation condition of the simulation calculation, and the atmospheric pressure is set to 101.3 kPa, the ambient temperature is 25 °C, and the air humidity is 30%. The opening temperature of the thermostat is 82 °C, and the full opening temperature is 95 °C. The simulation time is 1183 second, and the simulation step length is 1 second. Under NEDC operating conditions, the simulation results of the coolant and lubricating oil temperature changes are shown in fig. 6.

It can be seen from fig. 6 that as the vehicle speed changes, the temperature of the coolant and lubricating oil continues to rise over time. The coolant's maximum temperature is around 83 °C, and the maximum temperature of the lubricating oil is around 121 °C, which occurs during the period of 1000~1100 seconds speed increase. Under NEDC operating conditions, the simulation results of the coolant circulation flow rate and the inlet and outlet temperature of the radiator are shown in figs. 7 and 8.

It can be seen from figs. 7 and 8 that during the operation of the cooling system under NEDC cycle conditions, the thermostat is closed most of the time. The cooling cycle is small, and the coolant only circulates inside the engine. So that the engine can quickly reach operating temperature. At about 1050 seconds, the coolant's temperature exceeds the opening temperature of the thermostat by 82 °C, and the thermostat is opened. At this time, the coolant's large circulation is opened, and the coolant with a higher temperature flows into the radiator. With the action of the lower temperature coolant in the radiator and the radiator itself, the temperature of the coolant quickly stabilizes and no longer rises (after the 1050 seconds in fig. 7). Under NEDC operating conditions, the cooling fluid's heat dissipation simulation results are shown in fig. 9.

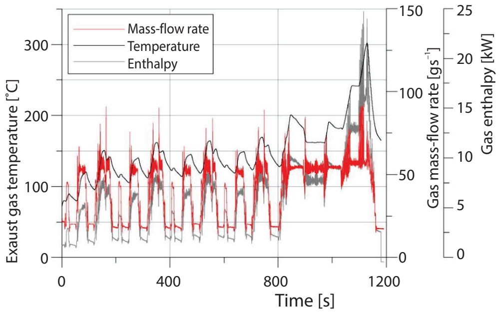

Figure 7. The NEDC working condition size circulating flow

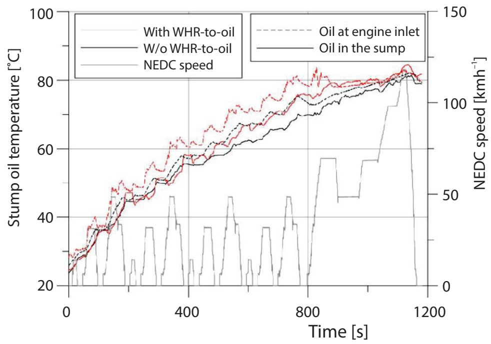

Figure 8. The NEDC operating condition radiator inlet and outlet temperature

It can be seen from fig. 9 that the heat transferred to the coolant changes with the engine speed. In the time range of 0 second to 1100 seconds, the coolant heat dissipation flow basically fluctuates below 15 kW. After the 1100 seconds, the engine speed reaches the maximum value. The heat flow of the liquid also reached the maximum, 23.4 kW.

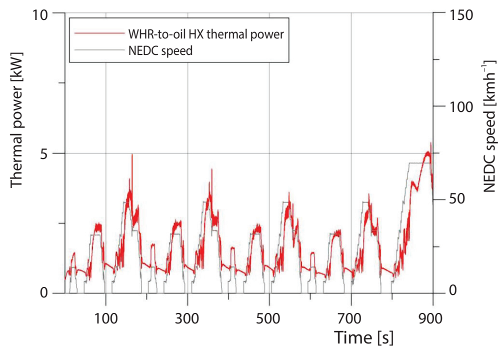

Figure 9. Coolant heat dissipation in NEDC working condition

Conclusion

The thesis obtains the heat dissipation of engine coolant circulation, the heat dissipation of lubricating oil circulation, and the heat generated by friction through engine thermal management's bench test in steady-state and transient state. The paper uses KULI simulation software to establish the engine thermal management system model and simulates the cooling system's performance under the NEDC cycle. The engine thermal management system test platform established by comprehensively considering the vehicle cooling system's structural factors can study the operational characteristics of the cooling system components such as water pumps, fans, and water tanks, while providing sufficient test data for simulation modelling. We use the cooling system's performance simulation results under the NEDC cycle to further study measures to shorten the engine start-up warm-up time, reduce fuel consumption, and optimize the cooling system.

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