Thermal analysis of cooling module based on engine test of thermal balance

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Abstract. Vehicle thermal analysis plays an important role of the overall vehicle development process. To determine energy distribution transformed from the heat released by combustion and build up the model to simulate heat transfer process of the cooling module, the engine bench was put forward to make thermal balance test and the drag test under vehicle target working conditions. It was found through the experiment data that the heat absorbed by the cooling system changed by the coolant temperature of the inlet. As a result, the correction map was established for the control system of cooling module that can be changed by the engine rotation speed, output torque and power value. A 1D -3D simulation model was built up by experiment data and coupling computing method. Based on the simulation model of cooling module that was verified by the thermal balance experiment data, the research and analysis were carried out on the performance of cooling module under the conditions of different environmental temperature and working state of air-conditioning system. The conclusion of interaction effects was made, which have important engineering value for the development of intelligent cooling module control system.

1. Introduction
Technology of vehicle thermal management (VTM) control and optimize heat transfer process to integrate cooling system, warm-up, thermal insulation system and climate control system (heating, air-conditioning and ventilating system) into an effective thermal management system to secure key parts and systems to work efficiently. Because of the different performance of key parts, subsystems, instruments and equipment and the complexity of vehicle environment and working state, the requirements of temperature, its change rate, gradient and limitation are diverse.

To evaluate the effect of VTM system, thermal balance analysis is always implemented by thermal balance test. Thus, optimized design scheme can be obtained to meet the requirements of improvement. thermal balance test was carried out to measure the heat flux to the coolant in the water jacket of the cylinder. Based on the test data, the cooling system was designed and matching, which would result in the cooling capacity surplus and poorly economic performance in case of analysis deficiency. Currently, studies on cooling system of engine are mostly focusing on the effect of the coolant temperature, working temperature of the cylinder body on engine power, emissions, fuel consumption etc. However, the engine rotation and load are affected by the working conditions directly, which are differential with the experimental data of engine thermal balance.

In this paper, energy flow and exchange between cooling system, transmission system, air-conditioning system and friction loss were studied in the respect of overall vehicle thermal management. Many factors were comprehensively discussed, such as coolant working temperature, engine load and rotation, to further the research on the heat absorbed by the cooling system. The correction map was
established for the control system of cooling module that can be controlled by the engine rotation speed, output torque and power value. Based on the controllable mathematical model, considering the complex effect factors, including air-conditioning system, outer environmental and driving condition, the working status of the cooling module were simulated by the overall vehicle thermal management-oriented model. The results can be used to develop intelligent control system of cooling module, which made the research more applicable and valuable.

2. Thermal Balance Test
The energy released by fuel combustion is converted into the following parts: output power of engine, friction loss, energy contained in the exhaust gas. The energy exchange processes are very complex during the operating of the engine because the heat in coolant, energy lost by friction and heat in machine oil can be transferred into each other.

![Figure 1. Schematic diagram of heat transfer process.](image)

a- Recycled heat from exhaust gas  
b- Heat transferred to intake air  
c- Heat transferred from exhaust gas to coolant  
d- Heat transferred from friction to coolant  
e- Heat radiated from exhaust gas  
f- Heat radiated from cooling system

Thermal balance and heat transfer in the engine are illustrated by Figure 1. It can be seen that the energy released from fuel combustion are divided into six parts at first. By heat transfer between subsystems and combination of energy loss, there are four categories of energy that can be tested during the experiment, which are heat energy discharged by the exhaust gas ($Q_{ex}$), heat carried off by the coolant ($Q_c$), energy transformed into effective power ($Q_{eff}$) and energy loss ($Q_l$).

To identify the amount of these categories of heat energy, it is necessary to build up a test bench. The test bench included engine, radiator, oil cooler, the core unit of air-conditioning. The scheme of the test system is shown in Figure 2. The coolant which flowed out the engine went through the branch pipes into the radiator and the heater of the cabin, respectively, and then was united at the entrance of the cooling circulation of the engine. The temperature of the coolant can be controlled by PID system. On the bench, many variables marked in Figure 2 should be tested by the equipment.
3. Test Results and discussion

From Figure 3, it can be found that proportion of $Q_l$ was very small, which constituted only less 4%, and the increase of $Q_l\%$ with the engine rotation speed was tiny. At the same time, $Q_{eff}\%$ and $Q_c\%$ decreased with the increase of the engine speed, except two fluctuation points near the speed of 2500r/min and 5000r/min. The maximum of $Q_c\%$ was over 20% at 1500r/min. The ratio of $Q_{eff}\%$ to $Q_c\%$ was over 3 when the engine speed was within 3500r/min to 5000r/min, among which the peak value appeared at 4500r/min.

In Figure 4, when the throttle valve was open, with the increase of engine rotation speed, $Q_{eff}$ and $Q_l$ increased evidently, while, the curve of $Q_c$ fluctuated at speed of 4500r/min. In the point of view to improve efficiency of VTM system, the results concluded above were meaningful which can reduce fuel consumption. The coolant temperature was controlled at 90°C, 95°C and 100°C, respectively. The test data indicated that $Q_c$ changed with engine speed and coolant temperature evidently, which was shown in Figure 5. When the coolant temperature was at 90°C, the heat exchange of the cooling module was about 40kW at the speed of 5000r/min. However, the heat exchange of the cooling module increased to about 50kW when the temperature was 100°C. The coolant temperature plays an important role in heat transfer process, so it should be paid attention on during the cooling module design.

![Diagram](image)

Figure 3. Relationship of energy proportion and engine rotation speed
4. Model setup and application

Based on the test data, the control system model of engine cooling module to calculate the released heat was established. As the vehicle was working, the model can be read base on engine rotation, torque and power after the ECU reads the signals of the accelerator pedal and analyzes the working state of the engine, which can forecast the energy transferred to the cooling system in the vehicle target working conditions. It has important application value for the development of intelligent control system for cooling module. The model of $Q_c$ when coolant temperature was 95°C. This model was set up based on vast experiment data and analysis. Because of the complexity of engine working conditions and interaction factors, including environmental temperature and air-conditioning supplemented heat, this map can be executed by the control system, which simplifies the calculation procedure and improve the precision.

To reduce calculation convergence cost and improve precision, a multi-dimensional coupled simulation method was proposed, which was 1D and 3D coupled model to achieve. integration of cooling system analysis and partial complex component computing. 3D model was set up by software STAR-CCM+ to simulate the flow resistant in the underhood, whose results would be more accurate than 1D calculation, as show in Figure 6. The actual structure of the underhood and components in it was simplified but still retains the important characteristics. Among them, due to the complex structure and calculation, the cooling fan was simulated by MRF model and the radiator is thought as porous medium model. Figure 7 showed calculation results of velocity vector contour.

The application of coupled model was demonstrated by the analysis on the effect of air-conditioning system. Because the structure of cooling module included two heat exchangers which are radiator and condenser. The heat transfer process in these two components was interactive, which was analyzed by the model. The comparison was shown in Figure 8-11 in different environment temperature and air-conditioning switch-on or off.
From the figures, it was found that the heat transfer was hardly affected by the environment temperature no matter what the air-conditioning state was, while the outlet coolant temperature changed sharply with the environment condition. The maximum differential value was 9 °C. With the increase of environment temperature, the mean air temperature of condenser increased as well. When environment temperature was the same, the differential value of air temperature in the condition of AC on/off was about 18 °C. The tendency of mean air temperature of radiator was similar with condenser, the differential value of air temperature in the condition of AC on/off was about 10 °C. The test data indicates that the requirements of cooling module turned to be strict when the environment temperature was 40 °C and AC was open.

The accurate simulation modeling with iterative coupling correction can make the simulation analysis and various optimization schemes, as well as, considering the different cooling air temperature, flow, engine affect, cabin temperature, and further predict their impact on the heat balance of the cooling system and evaluate the merits of design.

5. Conclusion

It is carried on the thermal balance test and the drag test in the vehicle working condition to get the energy distribution of combustion and the cooling system flow curve. The heat of coolant that combustion flow into the cooling system in different temperature is not the same.

It is found the phenomenon in different engine rotate that the energy of combustion into the cooling system.

Based on the data, it is established for the control system of engine cooling module model that can be read engine rotate, torque and power the three parameters when the ECU reads the signal to carry out forecasts the combustion energy flow to the cooling system in the target vehicle working conditions establish the cooling module heat release control system.
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