International Journal of Advances in Engineering and Management (IJAEM)
Volume 7, Issue 2 Feb. 2025, pp: 48-53 www.ijaem.net ISSN: 2395-5252

Optimization of front-end module matching design based on optimal energy consumption

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Date of Submission: 01-02-2025 Date of Acceptance: 10-02-2025

ABSTRACT: As a key component of the vehicle thermal management system, the design of the front-end cooling module has a significant impact on the overall energy consumption of the vehicle. This article focuses on improving fuel consumption through front-end module matching optimization design. The specific methods are as follows: 1. Adjust the intake to operate the cooling system at the optimal temperature; 2. Reasonably arrange the positions of low-temperature radiators and condensers to achieve the optimal level of air conditioning energy consumption and engine intake temperature affected by radiators; 3. Control and calibrate the engine water temperature reasonably through a low-temperature radiator. Based on the above methods, the optimization of vehicle energy consumption can reach 10%, which plays an important role in improving environmental protection and enterprise fuel consumption evaluation.

Keywords: Low temperature radiator; Condenser; Inlet temperature; Engine water temperature

I. INTRODUCTION

At present, as the global energy crisis continues to intensify and environmental awareness continues to deepen, the automotive industry is facing unprecedented challenges. As an important means of transportation in modern society, the energy consumption and carbon emissions of automobiles have become a global focus of attention[1]. How to effectively reduce energy consumption and carbon emissions while ensuring vehicle performance is not affected has become a key goal pursued by the global automotive industry.

As an indispensable and important component of the automotive structure, the front-end module is not only closely related to the aerodynamic performance of the entire vehicle, but also has a direct and crucial impact on fuel consumption[2]. Therefore, it is particularly important and urgent to carry out front-end module matching design based on the principle of optimal energy consumption.

In recent years, automobile manufacturers have continuously increased their research and development investment, striving to explore various technologies and methods to reduce energy consumption. However, current research in the industry mainly focuses on reducing energy consumption under normal temperature conditions[3], with relatively little research on optimizing energy consumption in high-temperature environments, and mainly focuses on the development of efficient air conditioning technology[4]. The depth and breadth of research in the field of thermal management still need to be further expanded.

Analysis of Factors Affecting High Temperature Energy Consumption

1.1 Logic diagram of high temperature energy consumption impact

Compared to normal temperature conditions, vehicles consume more energy at high temperatures. To better illustrate the reasons for the increase in high temperature energy consumption, a logical diagram of the impact on high temperature energy consumption is drawn, as shown in Figure 1 below:

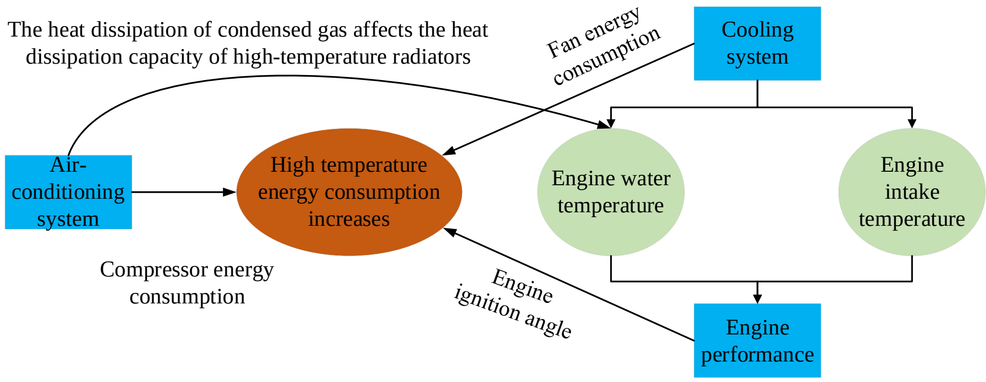


Figure 1 Logic diagram of the impact of high temperature energy consumption

From the above figure, it can be seen that under high temperature conditions, the vehicle needs to continuously rely on the cooling system to accurately control the engine water temperature and intake temperature during operation, in order to ensure the stability and completeness of engine performance. The cooling system takes away the heat generated by the engine through circulating coolant, and the fan plays an important role in this process by accelerating heat dissipation through forced convection. However, the operation of the fan requires the consumption of electrical energy, which inevitably increases energy consumption.

At the same time, the air conditioning system also participates in controlling the engine water temperature. The compressor in the air conditioning system is the main energy consuming component. When the compressor is working, it requires a large amount of energy to drive the refrigerant cycle, thereby achieving the cooling effect. In addition, the placement of the condenser in the air conditioning system can also affect the entire heat dissipation process.

The change in engine ignition angle will also have an impact on energy consumption. The adjustment of ignition thrust angle is an optimization strategy implemented by the engine control system based on the operating conditions of the engine. In high temperature environments, in order to avoid problems such as engine overheating and detonation, the ignition angle may be delayed. However, delaying the ignition angle can lead to a decrease in engine combustion efficiency, resulting in an increase in fuel consumption[5].

In summary, the increase in high-temperature energy consumption is mainly determined by three key factors: air conditioning system, cooling system, and engine performance requirements. These three factors are interrelated and influence each other, together forming a complex energy consumption system.

1.2 Explanation of Energy Consumption Impact of Each System

The increase in energy consumption of air conditioning systems is mainly composed of two parts. Firstly, in order to meet the cooling needs of the passenger compartment, the compressor must be activated. When the compressor is working, it requires a large amount of mechanical energy to compress the refrigerant and circulate it in the air conditioning system, thereby achieving heat transfer and cooling effect. This part of energy consumption will directly increase accessory power consumption, leading to an increase in overall vehicle energy consumption. Secondly, the placement of the condenser in the air conditioning system is crucial. The main function of the condenser is to dissipate the heat in the refrigerant to the external environment. If the condenser is not arranged properly, such as poor ventilation or insufficient heat dissipation area, it will affect its heat dissipation capacity. The decrease in the heat dissipation capacity of the condenser will lead to an increase in the temperature of the refrigerant, thereby affecting the refrigeration efficiency of the entire air conditioning system. In order to maintain the cooling effect, the compressor needs to work more frequently, thereby consuming more energy. At the same time, changes in the heat dissipation capacity of the condenser will also affect the heat dissipation capacity of the high-temperature radiator. The high-temperature radiator is responsible for cooling the engine coolant. If the condenser has poor heat dissipation, it will cause the temperature inside the engine compartment to rise, thereby affecting the heat dissipation effect of the high-temperature radiator. The decrease in the heat dissipation capacity of high-temperature radiators will cause an increase in the temperature of the engine coolant. In order to maintain the normal operating temperature of the engine, the cooling fan needs to increase its speed, further increasing energy consumption.

Air conditioning energy consumption=energy consumption of compressor+blower+electronic fan+water pump cooling system. Excessive engine water temperature and intake temperature will cause the ignition angle of the engine to be delayed, making it impossible for the engine to operate in the optimal air-fuel ratio range, resulting in a deterioration of the engine fuel consumption map. The air conditioning system provides sufficient ventilation to cool the engine coolant in the water tank, allowing the engine to operate at normal water temperature. The engine water temperature and the target engine intake temperature determine the pulse width modulation (PWM) duty cycle of the electronic fan. Therefore, PWM=f (engine water temperature, intake temperature) for the electronic fan. This adjustment method allows the cooling fan to adjust its speed according to actual needs, thereby improving engine combustion efficiency and reducing energy consumption.

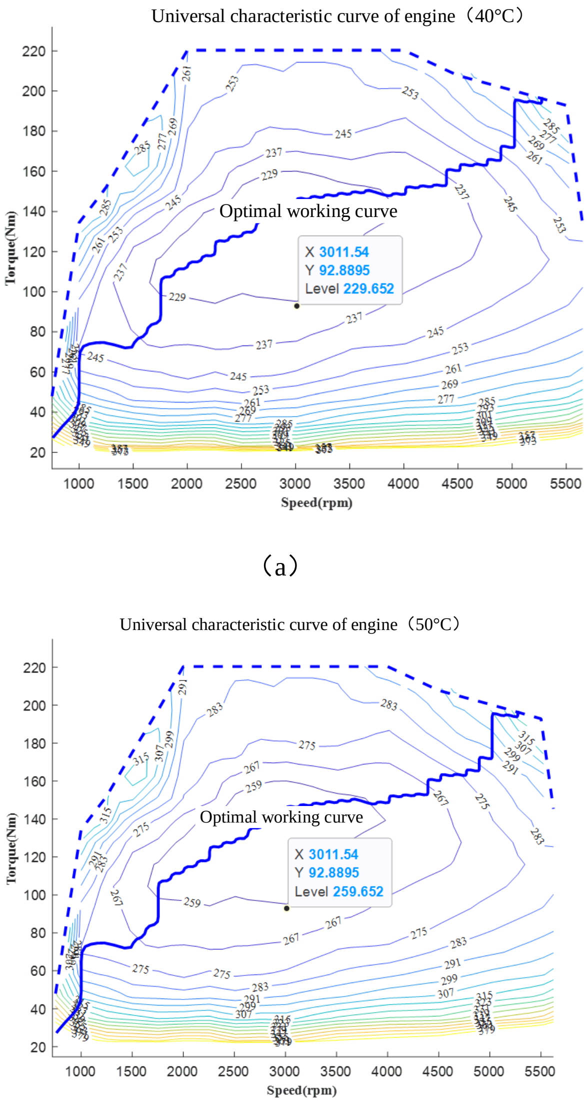
The energy consumption of the cooling system is equal to the power consumption of the electronic fan and the water pump. After the car operates at high temperatures, the electronic fan and water pump will work to cool down the engine and other components, resulting in an increase in power consumption.

Engine energy consumption=fuel consumption at high temperatures. The change in engine map at high temperatures is mainly due to the increase in engine intake temperature and water temperature, which leads to an increase in engine ignition angle and fuel consumption.

The deterioration degree of Brake Specific Fule Consumption (BSFC) of a certain engine at an intake temperature of 40 ℃/50 ℃ is shown in Figure 2 (due to the limited stability control of the intake temperature on the test bench, only some commonly used operating points are tested below).

The coil in the following figure represents the BSFC fuel consumption curve of the engine, and the blue line represents the optimal operating line of the engine, which is the best fuel economy that can be achieved when the engine is working.

Figure a shows the fuel consumption BSFC at an intake temperature of 40 degrees Celsius, while Figure b shows the fuel consumption BSFC at an intake temperature of 50 degrees Celsius; From the comparison of figures a and b, it can be seen that under the same engine speed of 3000rpm and torque of 92Nm, the BSFC with a 50 degree Celsius intake temperature is about 12% lower than that with a 40 degree Celsius intake temperature. Therefore, controlling the engine intake temperature will significantly improve fuel consumption.



(b)

Figure 2 Engine BSFC

II. OPTIMIZATION OF COOLING SYSTEM DESIGN

Figure 3 shows the cooling system design of a certain basic vehicle model, which uses a high-temperature liquid cooled radiator (HTR) to cool the turbocharged engine and a low-temperature liquid cooled radiator to cool the electric drive system; After high-pressure adiabatic compression by a turbocharger, the temperature of the intake air of a turbocharged engine rises sharply. To avoid high-temperature detonation, an air cooler is used for cooling.

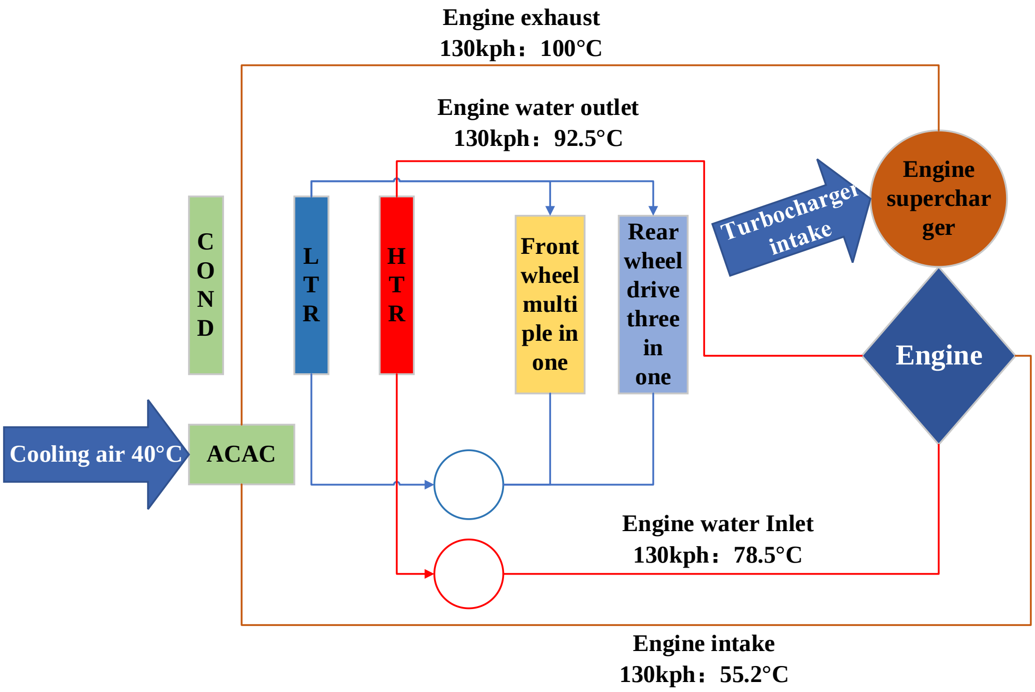


Figure 3 Original cooling system design diagram

It can be seen from this that the original design has obvious shortcomings. In the original design scheme, air was used as the direct cooling medium, resulting in significant fluctuations in the engine intake temperature. This is due to the design of the intake system failing to effectively control the stability of the intake temperature. The instability of intake temperature can easily trigger the ignition advance angle to retreat. The ignition advance angle is the advance of the engine ignition timing relative to the piston reaching the top dead center. The change in ignition advance angle will directly affect the combustion process of the engine. When the ignition advance angle is reversed, the combustion process becomes delayed, resulting in a decrease in engine power and poorer fuel economy. Meanwhile, incomplete combustion can worsen engine emissions, further affecting the environment.

New plan: Adopting water-cooled intercooling, with high water temperature and heat capacity, stable intake temperature, and low intake resistance of Charge Air Cooler (WCAC), the turbocharger load is small, improving fuel economy.

After considering the energy consumption at high temperatures, the cooling system was optimized to use coolant as the direct cooling medium. The large heat capacity of the coolant can prevent the engine intake temperature from changing with vehicle speed and engine thermal load, effectively stabilizing the engine intake temperature. The design is as follows: The water-cooled intercooler absorbs heat by utilizing the high heat capacity of the coolant.

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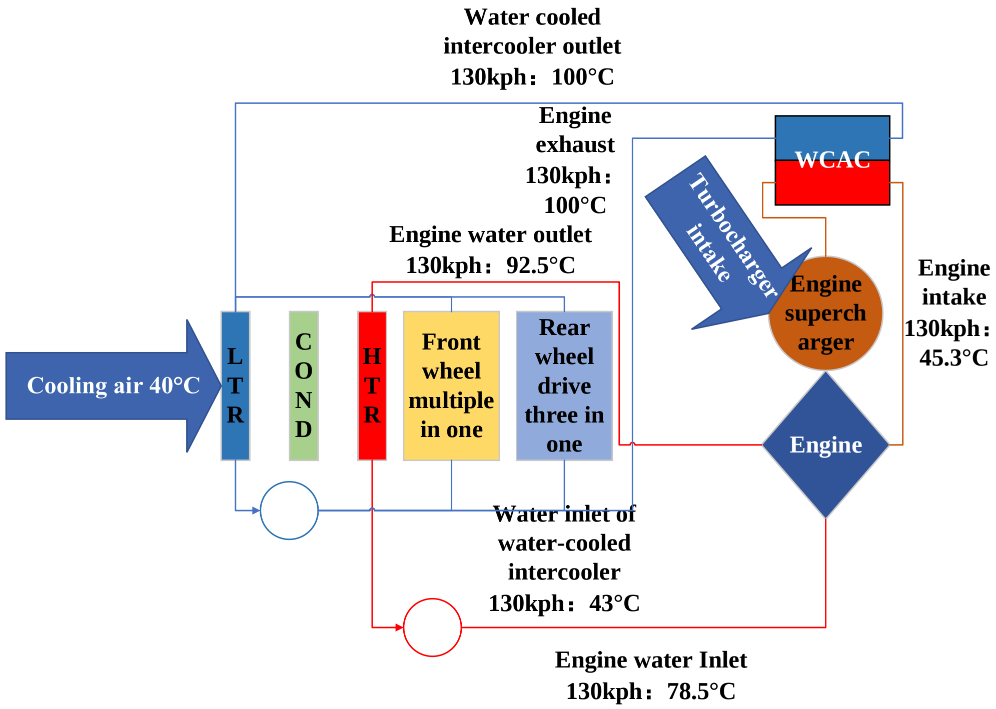

Figure 4: Optimized Cooling System Design Diagram

The comparison results between the optimized cooling system and the original system are shown in Table 1. It can be seen that the engine intake temperature in the original scheme is significantly higher than that in the water-cooled scheme, resulting in the passive delay of the ignition advance angle of the engine and the suppression of detonation tendency. After optimization, the large heat capacity of the coolant is utilized to increase the heat absorption capacity and effectively reduce the engine intake temperature.

Table 1 Scheme Comparison

Scheme comparison intake temperature	Engine water temperature	Intake temperature
Original plan	92.5	50
Optimization Plan	72.9	40

III. EXPERIMENTAL TESTING

In order to accurately evaluate the impact of different cooling design systems on energy consumption, it is necessary to control a single variable for testing and verification.

3.1 Experimental Design

1. In order to compare the performance degradation of high-temperature engines and the energy consumption of cooling systems, the experimental design is as follows:

$$FE_1=FE_2-FE_3 (1)$$

$$P_1=P_2-P_3 (2)$$

Among them: FE_2 represents the fuel consumption value per 100 kilometers at 130kph without air conditioning at an ambient temperature of 40 ℃, expressed in liters per 100km; FE_3 represents the fuel consumption value per 100 kilometers at 130kph without air conditioning at 25 ℃; P_2 represents the accessory power consumption of 130kph without air conditioning at an ambient temperature of 40 ℃; P_3 represents the accessory power consumption of 130kph without air conditioning at an ambient temperature of 25 ℃.

2. In order to compare the energy consumption of air conditioning systems, the experimental design is as follows:

$$FE'_1=FE'_2-FE'_3 (3)$$

Among them: FE'_2 represents the fuel consumption value per 100 kilometers at 130kph with air conditioning on at an ambient temperature of 40 ℃; FE'_3 represents the fuel consumption value of 130kph per 100 kilometers at 40 ℃.

The above experiments were all conducted on the conversion bench, with an ambient temperature of 40 ℃ and a simulated sunlight intensity of 850 W.

3.2 Test Results

The test results are shown in the following table:

Table 2 Comparison of Plans

130kph	FE_3	FE_2	$FE_2^{'}$
Original plan	9.54	10.03	12.23
Optimization Plan	8.59	9.19	10.83

As shown in Table 2, an increase in ambient temperature or turning on air conditioning can significantly increase fuel consumption. The cooling system designed in this article shows significant optimization effects in the following two aspects: when the air conditioning is turned off and the ambient temperature remains unchanged, the fuel consumption per 100 kilometers is reduced by 9% and 8.3% in environments of 25 ℃ and 40 ℃, respectively; When the air conditioning is turned on at 40 ℃, the fuel consumption per 100 kilometers is reduced by 11.4% compared to the original plan. Therefore, this plan can not only reduce fuel consumption during normal driving, but also effectively improve fuel consumption performance under air conditioning conditions.

IV. CONCLUSION

This study comprehensively analyzes existing energy consumption optimization technologies and proposes an innovative energy-saving strategy. Through the latest front-end module matching optimization design, it successfully achieves a significant reduction in energy consumption in high-temperature scenarios. The experimental results show that this strategy can save about 10% of energy consumption compared to traditional designs, while maintaining stable system performance. Although this study has certain limitations, such as a limited sample size, the research results still have important practical significance. In the future, we will apply this strategy to more vehicle designs and further optimize their performance, contributing to the realization of a green economy and sustainable development.

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