Artificial Intelligence Technologies and Applications
C. Chen (Ed.)

doi:10.3233/FAIA231334

Analysis of Automotive Thermal Management System Using One-Dimensional Simulation

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Abstract. This article takes the cooling system of a certain vehicle as the model and applies simulation tools to establish its cooling system and front cabin air side model. It inputs boundary conditions such as the flow resistance characteristics of each component. Then, it completes the steady-state simulation calculation of the vehicle system under different working conditions and optimizes the design of the original cooling system model. Calculating through simulation, we obtain the flow rate, pressure distribution, and temperature rise of the system and various components. We predict and evaluate the working capacity of the cooling system and propose improvement suggestions based on the calculation and analysis results. This plays an important guiding role in the structural design and testing of the cooling system, greatly reducing research and development time and reducing research and development costs. The calculation results show that the flow rate of each component in the rated point, heating test condition, and idle condition of the original plan has decreased compared to a certain model on the same platform under the same working condition. The temperature difference between the radiator and the flow rate of the oil cooler does not meet the specification requirements. It is recommended to continue optimizing the design.

Keywords. cooling system; flow resistance; characteristics; simulation

1. Introduction

The engine cooling system is a device that promptly removes the heat generated by high-temperature parts of a car engine during operation, ensuring that they operate within a normal temperature range. The cooling system should prevent both engine overheating and engine overcooling in winter. After the engine is cold started, the cooling system also needs to ensure that the engine heats up quickly and reaches normal operating temperature as soon as possible [1]. If the engine overheats, the mechanical strength of the components will decrease, and the normal fit clearance will be damaged. In severe cases, it will prevent the engine from working properly. If the engine is too cold, it can cause poor gasoline atomization, increased fuel consumption, decreased power, and increased wear [2].

The cooling system is an important component of automobiles, and its function is to ensure that the engine operates at the most suitable temperature under all working conditions. The suitability of the cooling system directly affects the engine's service life

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and fuel economy [3]. The ideal working state of an engine is that the cylinder head temperature is low and the cylinder body temperature is relatively high. A lower cylinder head temperature can improve inflation efficiency and increase intake volume. Low temperature and large intake can promote complete combustion, reduce the formation of CO, HC, and NOx, and also increase output power [4]. A higher cylinder block temperature will reduce friction loss, directly improve fuel efficiency, and indirectly reduce peak pressure and temperature in the cylinder. The cooling system is developing towards a controllable cooling system, allowing us to accurately design the cooling system from the perspective of energy distribution. The application of on-off water pumps, electric water pumps, electronic thermostats, etc., has reduced fuel consumption by about 2-3%, and diesel engines have reduced NOx by about 10-15%. Adopting a split flow water jacket, accurately designing the size of the cooling water jacket, reasonably matching the coolant flow rate, and ensuring that the system's heat dissipation capacity can meet the heat dissipation needs of key areas at low speeds and high loads [5]. It can cause a temperature difference of 100°C between the cylinder head and the cylinder block, reduce the friction loss of the cylinder block, and reduce fuel consumption. The higher cylinder temperature reduces fuel consumption by 4%-6% and HC by 20%-35% under partial load. According to the engine load, the coolant temperature is set, and the water jacket flow during warm-up conditions is reduced. This can achieve the goal of shortening warm-up time, reduce fuel consumption and emissions, and optimize energy distribution [6].

A certain vehicle model has been upgraded while upgrading its emission level. Based on the changes in the structure and performance parameters mentioned above, the entire vehicle's cooling system has also been changed. The cooling system has been recalculated and evaluated according to the requirements. This article mainly uses simulation analysis software to establish a 1D simulation analysis model for the cooling system of this vehicle model. The calculation and analysis focus on evaluating the flow rate, pressure distribution, and temperature rise of the system and various components. They also focus on predicting and evaluating the working capacity of the cooling system and proposing improvement suggestions based on the calculation and analysis results.

2. Overview of Simulation Analysis

The evaluation and analysis of fluid dynamics, engine heat dissipation, and cooling system heat dissipation are important bases for cooling system calculation and analysis.

2.1. Hydrodynamic Governing Equation

Fluid dynamics control equation:

When a car is running, its speed is far lower than the speed of sound. As a continuous medium, air can be regarded as viscous, incompressible, and adiabatic. In the calculation process of the external flow field, it is not necessary to solve the energy conservation equation. However, due to the presence of cooling components in the cabin, there is heat exchange. Therefore, in addition to solving the mass conservation equation and momentum conservation equation, the energy conservation equation must also be solved [7]. The Conservation of mass is the premise of satisfying various flows. This law can be summarized as: in unit time, the increase of fluid mass in the microelement is the same as the net mass flowing into the microelement in the same time interval. The fluid in this paper is incompressible, so it is deduced according to the mass conservation equation:

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=0 \tag{1}$$

The Conservation of momentum is also the basic law that all flow systems need to meet. The external resultant force that the fluid element can receive is equal to the rate of change of the momentum of the fluid element over time. In this paper, the fluid viscosity is steady and incompressible [8], so according to the Conservation of momentum, it is deduced as:

$$\frac{dv}{dt}=\frac{\mu}{\rho}\nabla v-\frac{1}{\rho}\nabla p \tag{2}$$

The conservation of energy can be expressed as: the net heat, surface force, and physical force entering the microelement doing work on the microelement equal to the rate of increase in energy in the microelement [9].

$$\frac{\partial \rho T}{\partial t}+div(\rho uT)= div(\frac{k}{Cp}gradT)+S\tau \tag{3}$$

2.2. Engine Heat Dissipation

The cooling system is an important part of the engine composition, and its performance directly affects the power, economy, and reliability of the engine. Generally, the circulating cooling water of the engine is required to reach a temperature between 80°C and 85°C after being cooled by the radiator. Low-power diesel engines operate between 75°C and 85°C. High-power diesel engines operate between 85°C and 90°C. The gasoline engines operate between 85°C and 95°C. The temperature of the cooling water entering the engine should not be lower than 40°C; otherwise, a series of chemical reactions will occur during the combustion process of the fuel, producing corrosive gases, causing cavitation on the engine cylinder block, and causing insufficient engine power [10]. The required heat dissipation parameters for the cooling system are mainly determined by a theoretical comprehensive calculation method.

For the fan and radiator group to perform their expected functions, it is necessary to conduct a comprehensive calculation of the cooling capacity.

- The total heat that must be dissipated by the radiator is determined.
- The theoretical air flow rate of the radiator is determined using the performance curves of the fan and radiator.
- The airflow rate is corrected based on the efficiency of the cooling system.
- The air-water temperature difference at which the radiator dissipates all heat is determined.
- The water temperature drop through the radiator is calculated.
- The temperature of the design environment is determined.
- The water temperature of the water chamber when working in the design environment is calculated.

In the heat load calculation, the heat load of the radiator includes the heat released by the engine to the cooling system after correction for ambient temperature and intake air temperature, plus the heat load of any cooler with the engine coolant as the medium. The heat dissipation capacity of an engine is generally the specified heat dissipation capacity at rated speed and maximum torque. If there is no sustained heat, heat dissipation at maximum power is considered.

2.3. Evaluation and Analysis of Cooling System Heat Dissipation

Based on experience, approximately one-third of the heat generated by fuel contributes to mechanical work. One-third of the thermal energy is discharged with the exhaust gas. One-third of the thermal energy is carried away by the cooling water, and the energy distribution is shown in the figure 1.

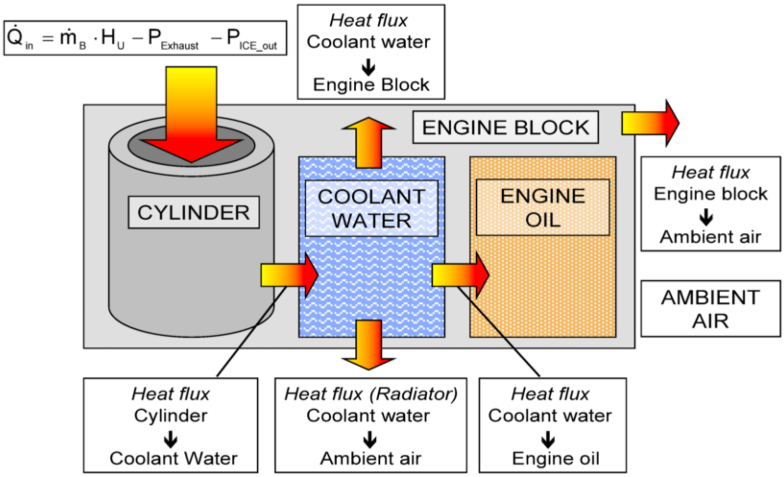

Fig. 1 Energy distribution map

The scatter plot of engine power vs. heat exchange shows that based on the above theory, the system heat exchange of this project is estimated to be 80 kW, and the trend of engine power vs. heat exchange is consistent with the experimental data.

3. Simulation Calculation Analysis

3.1. Analysis Overview

3.1.1. Cooling System Simulation Objectives

The development goals of the cooling system mainly include meeting the cooling needs of various systems (users) and optimizing energy distribution reasonably. The cooling system has no boiling phenomenon, and all components have no overheating. The water jacket has no dead zone, and the distribution of flow rate and heat transfer coefficient is reasonable. There is no cavitation phenomenon in the cooling system (water pump). It has a short degassing time and an initial filling rate greater than 90% of the system volume. The opening temperature setting of the thermostat is reasonable. There is a short warm-up time, low fuel consumption, and low emissions. The working temperature of the cylinder head is low, while the working temperature of the cylinder block is high. It has better passenger comfort (heating). The cooling system consumes less power from the engine. It is reliable with long service life and low manufacturing cost.

3.1.2. Engine Parameters

According to project requirements, a simulation analysis of the cooling system is required. The engine power of this project is 135 kW, and the maximum torque is 270 N·m. The heat dissipation is evaluated as above. Simulation calculations are conducted on the main cooling cycle, and cooling system solutions are proposed. The engine parameters are shown in the table 1 below.

Table 1. Engine parameters

Name	Unit	Value
Engine model		Gasoline
Bore/Stroke	mm	Φ74.5/80
Firing order		1-3-4-2
Rated power/speed	kW/rpm	135/5500
Max.torque/speed	N·m/rpm	270@1500~4000 rpm

3.1.3. Cooling System Structural Layout

The geometric modeling of the whole vehicle cooling system simulation is composed of a water pump, high and low-temperature thermostat, machine cooler, intercooler, high and low-temperature radiator, fan, expansion tank, transmission oil cooler, heater, etc. The schematic diagram of the cooling system is as follow figure 2.

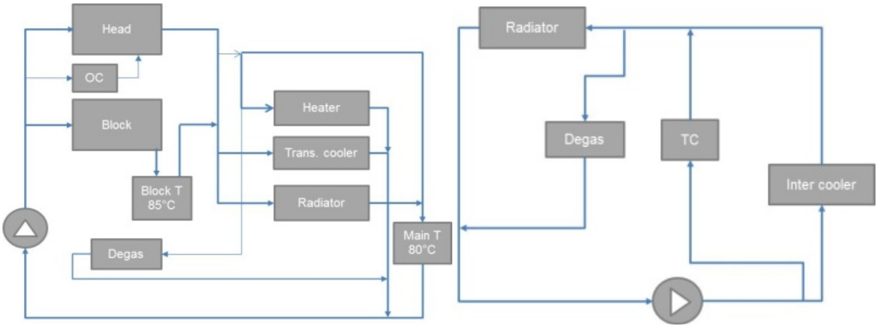

Fig. 2 Schematic diagram of cooling system principle

3.1.4. Cooling System Analysis Process

The simulation and experimental verification process of the engine cooling system described in this analysis is as follows:

(1) The cooling system components and heat dissipation data are determined and proofread based on experimental data. Parameterization processing is performed.

(2) A 1D dimensional cooling system calculation model is built.

(3) Calculations are simulated based on boundary conditions and different operating conditions.

(4) The calculation results are analyzed and evaluated to see whether they meet the expected design indicators.

When the calculation results do not meet the expected design indicators, the cooling system-related components are optimized, and Steps (1) - (4) are repeated. When the calculation results meet the expected design indicators, we output the optimization design results.

3.1.5. Analysis Specifications

The analysis specifications for this project are shown in the table 2 below:

Table 2. Analysis specifications

Part	Criteria	Mark
Radiator	△T is about10-11℃@5500 rpm	CAE criteria
Oil cooler	△T is about 8-10℃	
Transmission oil cooler	△T is about 6-8℃	Supplier requirement
Cabin heater	Flow >6 L/min@750 rpm. Flow >11.5 L/min@1500 rpm	Vehicle requirement
Water pump	200 L/min@23 m	Supplier requirement

3.2. Analysis Model

The main cooling cycle includes components such as water pump, engine water jacket, high-temperature thermostat, low-temperature thermostat, main radiator, heating, transmission oil cooler, auxiliary thermostat, and expansion water tank. The main cooling cycle analysis model is as follow figure 3.

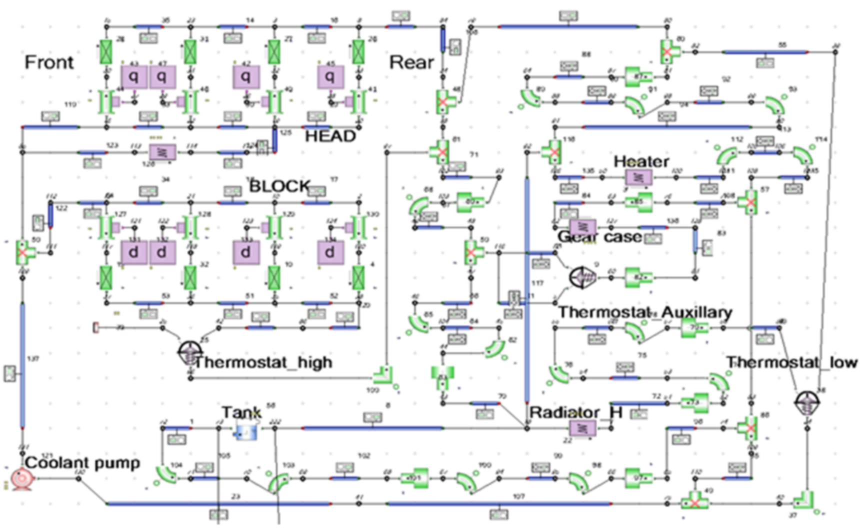

Fig. 3 Schematic diagram of cooling system principle

3.3. Main Analysis Inputs and Boundary Conditions

3.3.1. Water Pump

Water pump reference point: speed-6630 rpm, flow rate-160 L/min, head-16 m. The map characteristics of the water pump are shown in the following figure 4.

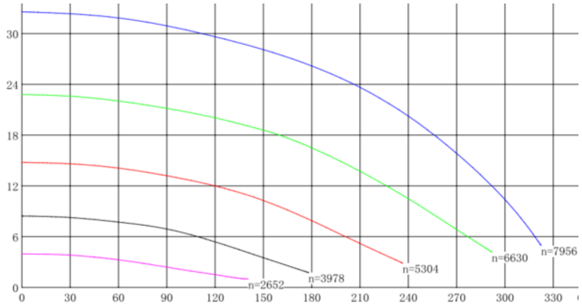

Fig. 4 Map characteristics of the water pump

3.3.2. Main Radiator

The main radiator reference point is 100 L/min@0.45 bar. The map characteristics of the main radiator are shown in the following figure 5.

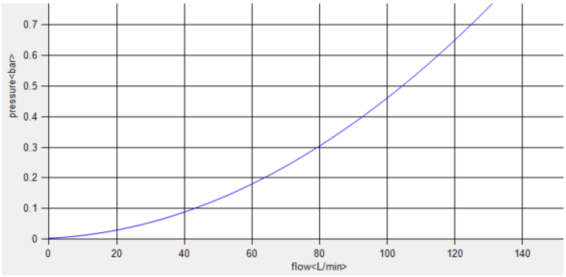

Fig. 5 Flow resistance curve of radiator

3.3.3. Air Heater

The air heater flow resistance curve is shown in the following figure 6.

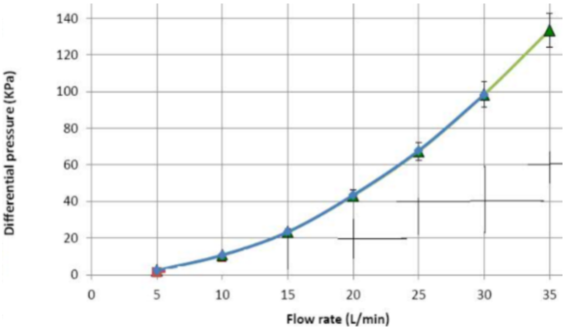

Fig. 6 Warm air flow resistance curve

3.3.4. Thermostat

The opening temperature of the low-temperature thermostat is 80°C, and the opening temperature of the high-temperature thermostat is 87°C,which is shown in the following figure 7.

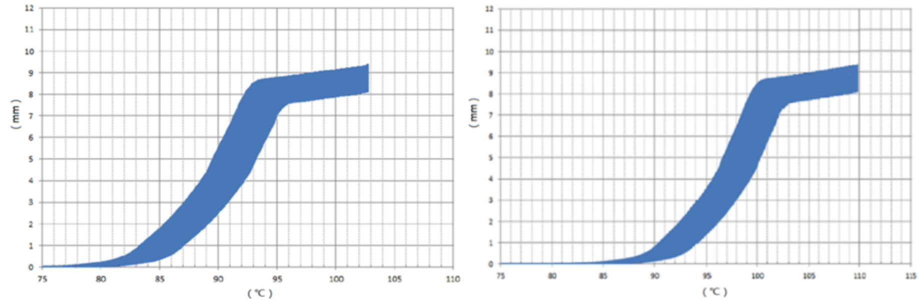

Fig. 7 Characteristics of low and high-temperature thermostats

3.3.5. Oil Cooler

The heat dissipation of the 1.5 T cooler is estimated to be 9% of the power value, approximately 12 kW. The flow resistance characteristics are shown in the following figure 8.

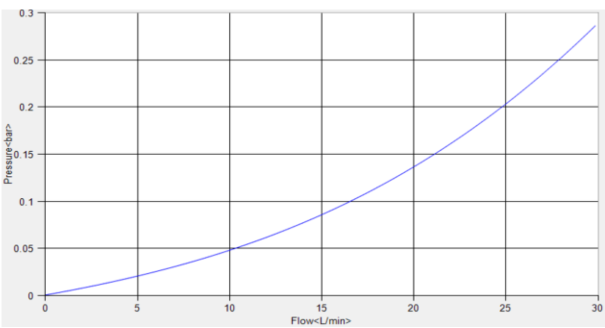

Fig. 8 Flow resistance curve of the oil cooler

3.3.6. Engine Water Jacket

To reflect the actual pressure drop characteristic parameters, in the 1D model, the resistance of the engine cooling water jacket is represented by discrete losses. Discrete loss is represented by voltage drop in software networks. According to the CFD analysis results, the flow resistance of the cylinder head water jacket is 51.3 kPa@123.7 L /Min; The reference point for the flow resistance of the cylinder block water jacket is 49 kPa@46 L /Min. The model is shown in the following figure 9.

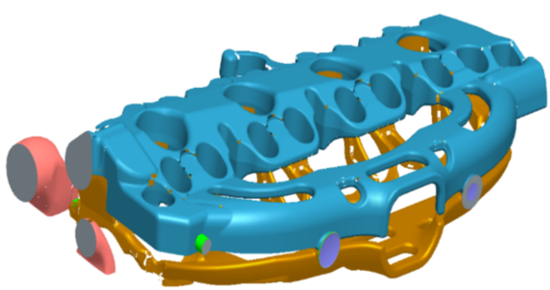

Fig. 9 Water jacket model

3.3.7. Cooling System Connection Pipeline

The diameter and length of the cooling system connecting the pipeline are shown as follow figure 10.

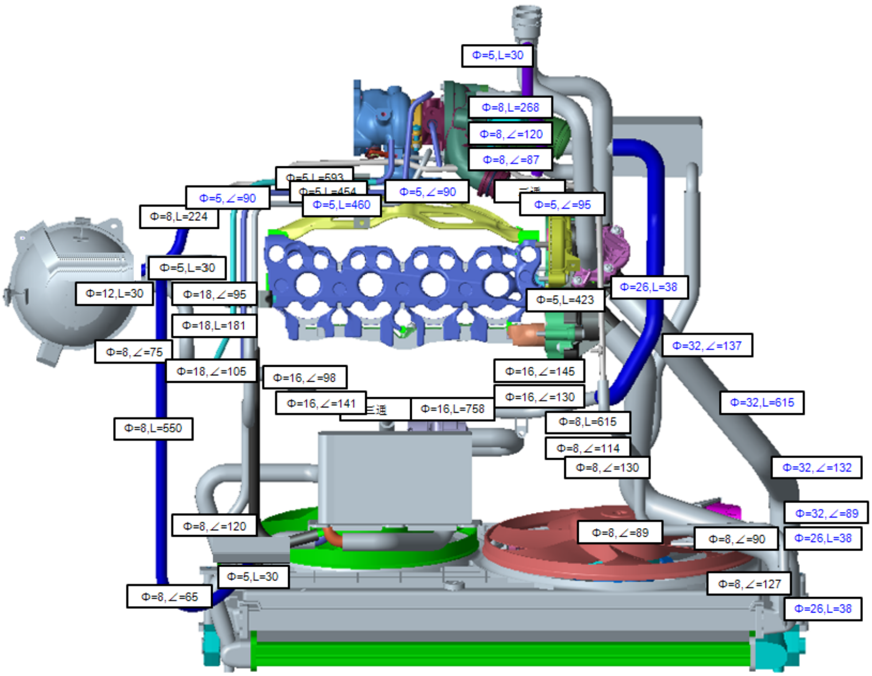

Fig. 10 Cooling system connection pipeline

4. Result Analysis and Evaluation

The model verification is completed, and the simulation results are as follow table 3.

Table 3. Simulation results

Part	Parameter	5500 rpm	4000 rpm	2500 rpm	1500 rpm		750 rpm	
					Hot	Cold	Hot	Cold
Pump	Flow (L/min)	163.5	113.5	70.3	36.3	25.2	21.6	14.4
	ΔP (bar)	1.8						
Radiator	Flow (L/min)	101.4	70.5	43.6	22.7		13.6	
	ΔT (℃)	13.5						
Oil cooler	Flow (L/min)	16.7	10.8	5.8	2.2	1.1	0.87	0.92
	ΔT (℃)	11.9						
Air heater	Flow (L/min)	36.1	25	15.4	7.8	9.3	4.5	5
Transmission oil cooler	Flow (L/min)	22.1	15.3	9.5	4.9	0.5	2.9	0.33
Expansion tank	Flow (L/min)	4.2	2.9	1.8	1	1.2	0.65	0.71

(1) Coolant Pump: The conclusion is that according to the current cooling circuit model, the pump capacity is 163.5 L/min @1.8 bar, which does not meet the analysis specifications.

Advice: The next step is to consider the optimization scheme, such as increasing the capacity of the pump for further calculation and analysis.

(2) Radiator: The temperature rise of the cooling water of the main radiator is 13.5°C, which exceeds the analysis specifications during summer working conditions.

Advice: A larger radiator capacity is required to meet the temperature difference. Using a pipe inner diameter=40 mm for the radiator is recommended to enlarge to 45 mm or 46 mm.

(3) According to the pressure drop characteristics provided by the supplier, the coolant flow is 16.7 L/min @5500 rpm. The temperature rise of the machine cooler is 11.9°C, which exceeds the requirements of supplier evaluation.

(4) Heater: The coolant flow is 9.3 L/min@1500 rpm and 5 L/min@750 rpm. The target for 1500 rpm and idle engine speed defined by the vehicle department both had not been reached.

Advice: Using a pipe inner diameter=16 mm for the cabin heater is recommended to increase to 20 mm. The actual coolant flow through the cabin heater should be checked on the test bed.

(5) The suggested heat transfer capacity of the radiator is 110 kW, so an optimization scheme should be considered.

5. Conclusion

The pipeline connection mode of the original plan is adopted. The flow rate and temperature rise of each component of the system are not reasonable. The idle warm air flow rate does not meet the specifications. The cooling system designed according to the above original scheme cannot meet the requirements of Euro VI vehicle exhaust emission standards. The characteristics of the system components, such as the water pump, radiator, machine cooler, warm air, and transmission oil cooler, need to be further confirmed by the design department. Further optimization scheme design needs to be considered.

In this paper, the simulation analysis software is used to establish the 1D simulation analysis model of the cooling system of this vehicle model, and the flow, pressure distribution, and temperature rise of the system and each component are evaluated in the calculation and analysis. The prediction and evaluation of the working capacity of the cooling system of the original scheme are made, and suggestions for improvement are put forward according to the calculation and analysis results, which are verified by experiments. The error between the simulation results and the test results is small. It is proved that the simulation accuracy is high, and the model can be used to calculate and analyze the next optimization scheme to meet the standard requirements of the cooling system design.

In the future, engine thermal management will be studied, which can fully play the function of the cooling system and integrate all the links that affect the engine cooling performance. It is of great significance to comprehensively improve the overall performance of the engine.

Acknowledgments

This work was financially supported by the R&D Program of the Beijing Municipal Education Commission (KM202310858005).

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