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Development of an Intelligent Thermal Management System for BYD DM-i Hybrid Engine

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Abstract

BYD recently introduced its new DM-i (Dual Mode-Intelligent) plug-in hybrid architecture with a new dedicated 1.5NA (Naturally Aspirated) high-efficiency engine, which can reach a peak of 43% brake thermal efficiency. With this architecture, the vehicle is mainly driven by motors and engine only starts when required. This requires that once started, the engine can reach its best working temperature as quick as possible. To achieve this target, a new intelligent thermal management system was designed. This system adopted an advanced split cooling strategy to control the flow ratio between cylinder block and head, which was realized by the combination of one electronic thermostat and one wax thermostat. An electronic water pump was used to actively control the coolant flow rate. Together with the intelligent control of thermal needs under all working conditions, the new thermal management system realized the following benefits: faster engine warm-up, better fuel economy and lower pollutant emissions. 1D (One Dimensional) simulation was used to optimize the flow ratio between cylinder block and head. By analyzing the flow distribution, temperature level and pressure drop of each component in the HT (High Temperature) loop and LT (Low Temperature) loop, the cooling performance of this new thermal management system was evaluated and optimized. 3D (Three Dimensional) simulation was used to optimize the flow channel design. Finally, the performance of the thermal management cooling system was validated on the engine test bench and the coolant temperature was calibrated for the whole engine map.

Introduction

The intelligent engine thermal management system is able to decouple the cooling system operation with engine speed. The traditional mechanical driven parts are replaced by electrical ones, such as electronic water pump, electronic thermostat and electronic fan, etc., so that the cooling performance can be precisely controlled with the optimized control strategy. The performance of the thermal management system is critical to realize good fuel economy and reduced emissions. A good engine thermal management system should be able to realize the following functions [1]:

1. Keep the engine working at the optimal temperature, reduce knock tendency and improve fuel economy.
2. Reduce the engine parasitic loss, shorten the warm-up time and reduce emissions.
3. Keep the optimal oil temperature to reduce engine friction and wear, increase the engine service interval and durability.

Lots of researches have been done in the last few decades on the intelligent engine thermal management system. Cipollone et al. [2] used 1D simulation to study the effect of double cooling circuits at different temperatures on engine performance. Results showed that the engine warm-up time can be reduced by 30% with 4%~5% benefit in fuel consumption. Castiglione et al. [3] proposed a Robust Model Predictive Control (MPC) methodology for quick engine warm up, which reduced 60% the coolant flow with the help of electronic water pump. Results showed that compared to the traditional cooling system, it took 180 seconds less for the cylinder wall to be warmed up to 120°C. Cortona et al. [4] designed and simulated the performance of two cooling system setup, one with an electronic water pump and a wax thermostat, another one with an electronic water pump and an electronic thermostat. Results were validated with bench test data. It was shown that the combination of electronic water pump and electronic thermostat can precisely control the coolant temperature, reduce the water pump energy consumption and achieve quick engine warm up. Choukroun et al. [5] developed an intelligent thermal management system consisting of an electronic water pump, an electronic thermostat and an electronic fan. The performance was checked by simulation and validated by wind tunnel test results. It was shown that this concept allowed a reduced warm-up time by 50% and 2%~3% fuel consumption on the NEDC cycle.

BYD introduced a new DM-i plug-in hybrid architecture recently, aiming to have an fuel consumption lower than 4.0 L/100 km. In order to meet the requirement, a new 1.5L DHE (Dedicated Hybrid Engine) was developed. The compression ratio of this new engine is 15.5, with 134 Nm rated torque at 4500 rpm and 81kW rated power at 6000 rpm.

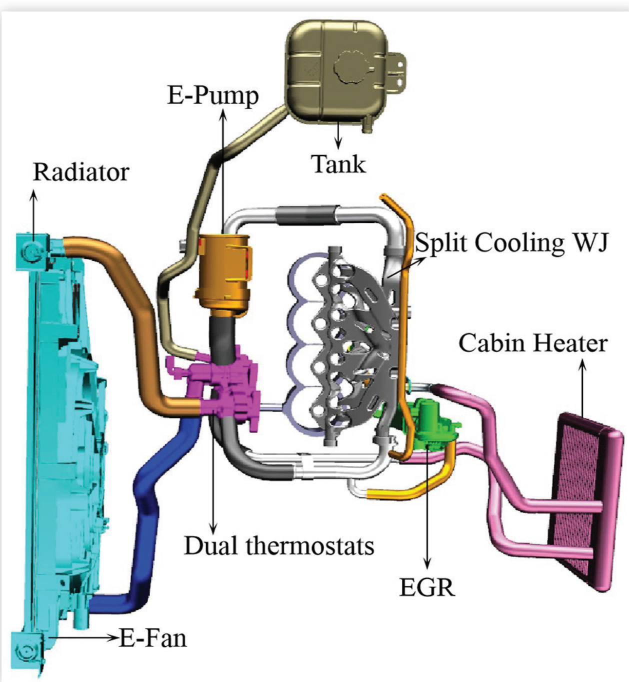
The above engine performance requirements put forward three main challenges for the thermal management system:

- High compression ratio leads to high knock tendency, which brings up new requirement for cylinder block and head design, especially for WJ (Water Jacket) design.
- The engine starts and stops frequently in DM-i plug-in hybrid architecture. So the engine needs to have the ability to preserve heat during intermittent engine usage.
- The engine will have performance and emission deterioration if it cannot be quickly warmed up to its working temperature during the cold-start and warm-up period.

Currently mainstream advanced thermal management systems are based on split cooling with either electronic thermostat or TMM (Thermal Management Module). With proper control strategies, it can realize accurate temperature and flow rate control of the cooling system. Split cooling with electronic thermostat can give 0.35% BTE (Brake Thermal Efficiency) benefit and 0.8% CO_2 reduction in WLTC cycle. Split cooling with TMM can give 0.45% BTE benefit and 1% CO_2 reduction in WLTC cycle. They are mainly adopted by OEMs (Original Equipment Manufacturer) in Europe, Japan and the United States [6].

But these two advanced thermal management systems cannot solve the need for heat preservation during intermittent engine usage and the benefit for fuel economy is limited. This paper shows the development process of a new intelligent thermal management system for the 1.5L DHE engine. As shown in Figure 1, this system adopted cylinder block/head split cooling system with an electronic WP (Water Pump) and two thermostats (one electronic thermostat and one wax thermostat). With 1D and 3D simulation, the best flow split ratio between cylinder block and head, the flow distribution and pressure drop of the cooling system was optimized. Together with intelligent control strategy, the engine was ensured to run at the optimal working temperature at all times including during intermittent usage.

FIGURE 1 Intelligent thermal management system.



Cooling System Design and Simulation

First the cooling circuit of the thermal management system is optimized with 1D and 3D simulation. The objectives are:

- To evaluate the performance of the electronic control hardware and select suitable components.
- To get the overall dimensions of the flow channels.
- To evaluate and optimize the flow distribution, temperature level, flow speed and pressure distribution in the cooling circuit.

1D Simulation Model Setup

Model-based design can reduce the risk of system design and shorten the cycle of product development [7]. The cooling system simulation model was set up using the 1D simulation tool FLOWMASTER based on the previous generation and adapted to the development goals of the new engine, as shown in Figure 2.

Pipelines were setup based on 3D CAD data. Available component pressure drop and flow information from either the database or CFD results were used as input. Some of the related boundary conditions are shown in Table 1.

FIGURE 2 1D cooling system simulation model.

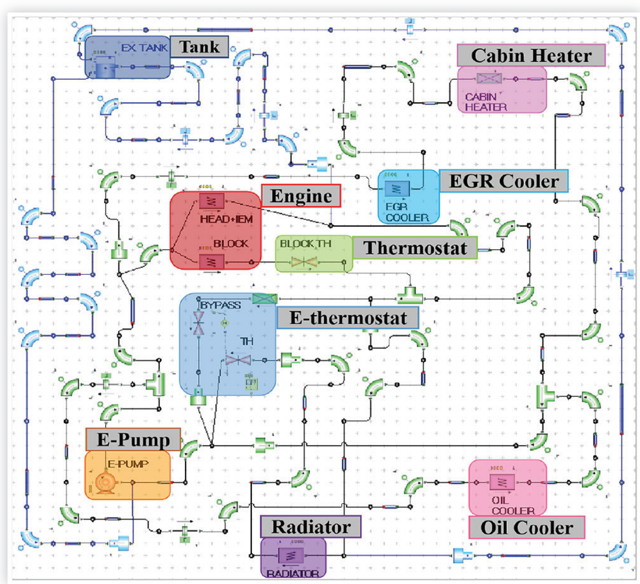


TABLE 1 1D simulation boundary conditions.

General input data			
1	Engine rated speed	6000	rpm
2	Engine rated power	81	kW
3	Maximum pump flow rate	113.4	L/min
4	Maximum coolant temperature	115.0	°C
5	Liquid type—water/glycol	50/50	v/v
Hydraulic performance			
6	Radiator pressure drop	28.1	kPa
7	Oil cooler pressure drop	7	kPa
8	Cabin heater pressure drop	11.59	kPa
9	EGR cooler pressure drop	6	kPa
10	E-Thermostat pressure drop	19.4	kPa
11	Wax thermostat pressure drop	1.5	kPa
Heat Input			
12	Engine heat input	42.3	kW
13	Engine head heat input	33.1	kW
14	Engine block heat input	9.2	kW
15	Oil cooler heat input	4.5	kW
16	Radiator heat rejection	46.8	kW

Selection of Electronic Water Pump

Electronic WP is the heart of the cooling system and affects the cooling performance directly. Based on the performance target of the cooling system, two electronic WPs were selected with the performance curves shown in Figure 3. In order to ensure sufficient margin of the electronic WP, the maximum cooling flow rate condition was simulated, which was at 6000 rpm engine speed when both thermostats were fully opened. Simulation results are shown in Table 2. For the same case, WP-1 was able to produce 1.8 L/min more flow and showed 1% higher efficiency compared to WP-2. Larger flow rate means the heat can be taken away faster and thus better cooling performance. Thus WP-1 was selected for test bench validation.

FIGURE 3 Performance curves of two electronic WPs.

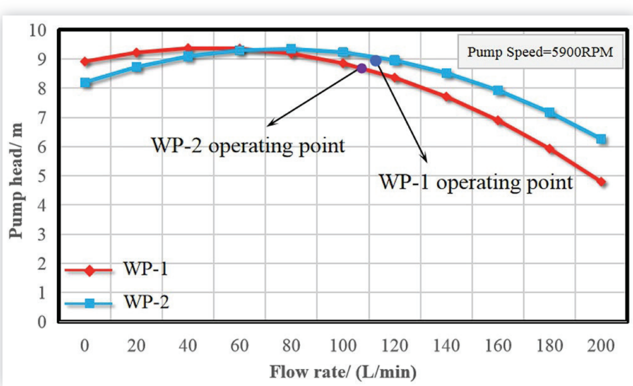


TABLE 2 Simulation results of two electronic WPs.

Index	electronic WP-1	electronic WP-2
Pump speed	5900rpm	5900rpm
Volume flow	113.4L/min	111.6L/min
Pump head	8.82m	8.89m
Pump efficiency	56%	55%
Pump power	0.29 kW	0.29 kW

Simulation of Water Jacket

The split cooling WJ mainly consists of upper cylinder head WJ, lower cylinder head WJ and cylinder block WJ. The coolant flow direction is: main inlet → lower cylinder head → upper cylinder head and cylinder block → cylinder head outlet and cylinder block outlet, as shown in Figure 4.

To analyze the performance of the water jacket design, 1D and 3D coupling simulation was performed. The pressure distribution at the coolant inlet and outlet of cylinder block and head is shown in Figure 5. Overall, the highest pressure was 245.2 kPa in the lower part of cylinder head. The pressure of cylinder block was the lowest, which was 215 kPa. The pressure gradient of the whole water jacket was moderate. The flow split ratio between head and block was 3 to 1, which is designed to give better cooling to the cylinder head, reduce knock tendency and exhaust temperature, thus giving better power performance and fuel economy. The pressure difference between the coolant inlet and outlet of the cylinder head was 20.8 kPa, and that of the cylinder block was 20.5 kPa, which were both within the design target (50 kPa) with reasonable flow resistance and energy loss.

The flow velocity distribution of the water jacket is shown in Figure 6.

Results showed that overall the flow velocity was between 0.1 m/s and 3 m/s, which met the design requirement (0.1m/s-5m/s). The small area of flow dead zones near the IEM (Integrated Exhaust Manifold) will not affect the overall flow. The flow velocity near the intake and exhaust ports was 1.3 m/s and distributed equably. The coolant flow was good in the nose bridge area with velocity around 3 m/s, which would help to avoid local over-heating [8]. The average flow velocity was 1.5 m/s between cylinder 1 and 4, and 0.8 m/s between cylinder 2 and 3. The velocity at the inner of WJ was larger than the

FIGURE 4 The coolant flow direction of the split cooling WJ.

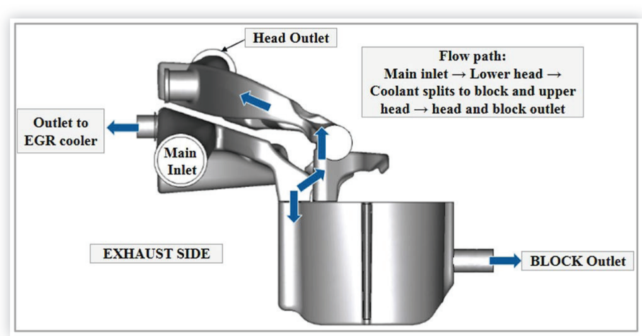
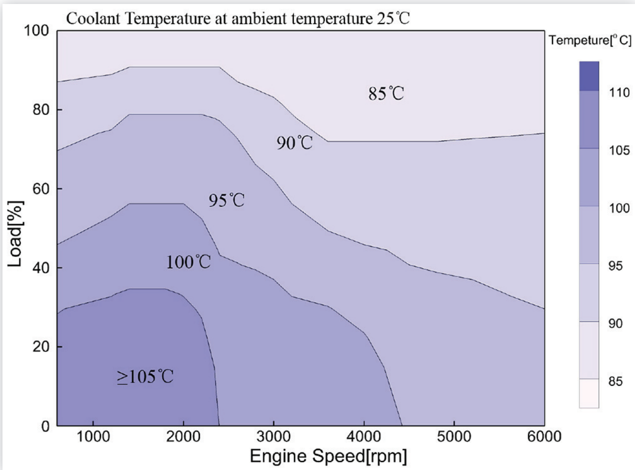


FIGURE 15 The engine coolant temperature map.



management control strategy, four efficient working modes are realized.

State One: Micro Coolant Flow

As shown in Figure 16, when the coolant temperature is below 30°C, the electronic water pump is controlled to be working at a very low speed. The wax thermostat and the electronic thermostat are both closed. The coolant flows through the cylinder head in minimum amount to heat the engine up quickly while keep the cylinder head from overheating. In this state, the coolant in the cylinder block doesn't flow.

FIGURE 16 The micro coolant flow circulation.

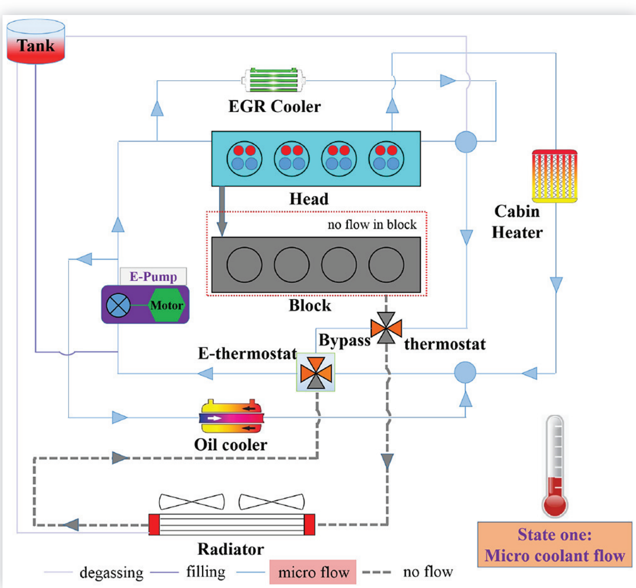
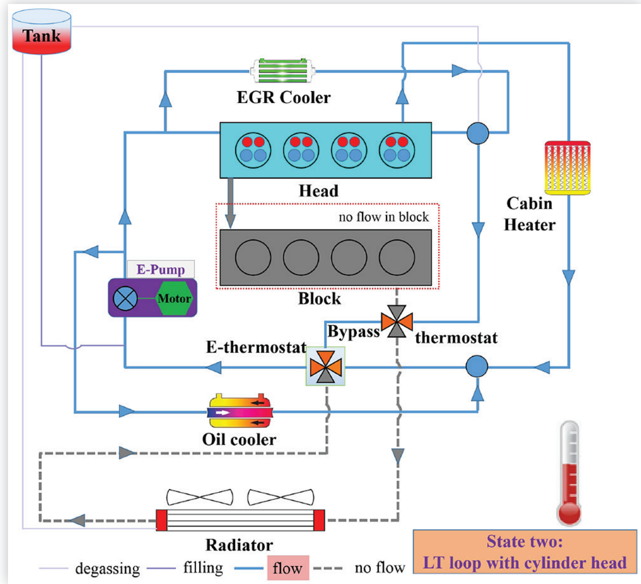


FIGURE 17 The internal circulation with cylinder head.



State Two: LT Loop with Cylinder Head

As shown in Figure 17, when the coolant temperature is higher than 30°C, the electronic water pump speed will increase. The coolant still flows only in the cylinder head. Both thermostats are still closed until the coolant temperature reaches 70°C.

State Three: Full LT Loop

As shown in Figure 18, when the coolant temperature rises to 70°C, the wax thermostat will open. The coolant flows both in the cylinder head and block. The electronic thermostat is still closed until the coolant temperature reaches 95°C.

FIGURE 18 The full internal circulation.

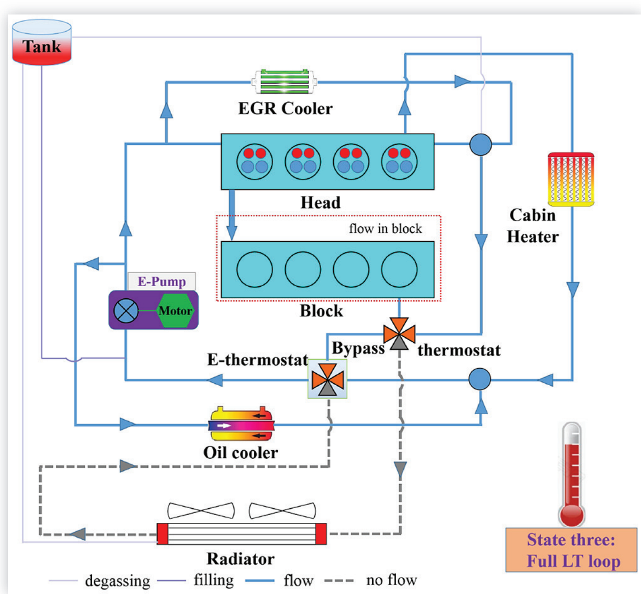
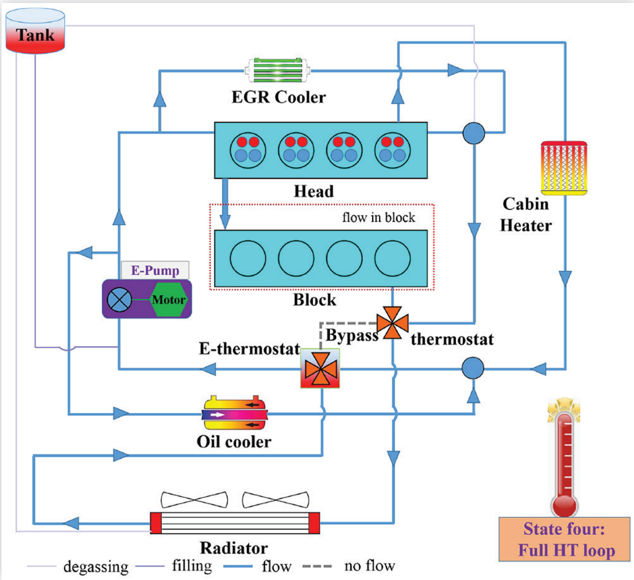


FIGURE 19 The external circulation.



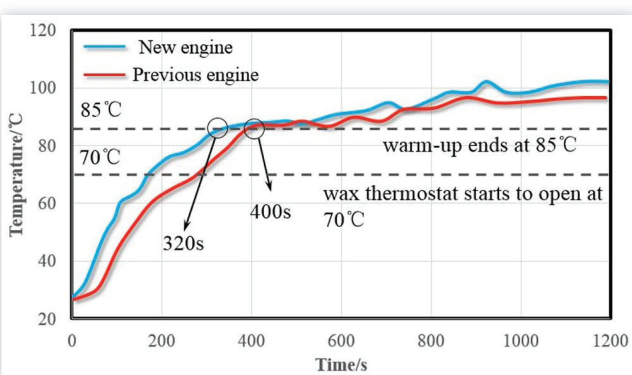
State Four: HT Loop

As shown in Figure 19, when the coolant temperature rises to 95°C, the electronic thermostat will open. In this state, the electronic thermostat and WP are used to accurately control the coolant flow rate so that the coolant can be always kept at the optimal temperature as calibrated.

At low loads, the coolant temperature is higher than 95°Cso the electronic thermostat opens naturally without additional heating. The electronic water pump runs at low speed to reduce its power consumption. While for the high load area, when the coolant temperature is below 95°C, the electronic thermostat turns on heating mode to keep the engine runs in HT loop.

Figure 20 shows the comparison of this intelligent thermal management system when applied to DM-i plug-in hybrid architecture and that of the previous generation with a wax thermostat and a mechanical water pump. The warm-up time is shortened by 20% while fuel consumption in the charge-sustaining WLTC cycle can be reduced by 1.3%.

FIGURE 20 The warm-up time comparison.



Conclusions

1. A new thermal management system was developed for BYD DM-i 1.5L DHE, including: split cooling of cylinder block and head, electronic WP, electronic thermostat and wax thermostat. Combined with intelligent control strategy, the thermal management performance was greatly improved.
2. 1D and 3D coupled simulation was adopted during the design process. 3D CFD provided the pressure drop, heat transfer coefficient for the 1D simulation and 1D simulation in turn provided flow rate boundary condition for the 3D simulation. The coupling of the 1D and 3D simulation improved simulation accuracy.
3. Simulation results were validated with thermal test bench data. Results showed good agreement within 10% difference. These results showed good accuracy of the 1D and 3D coupling simulation and it can be used to guide the thermal management system concept development with good confidence. The simulation model can also be used for future system upgrading to save cost and development time.
4. Coolant temperature map was calibrated, and four working states were realized. The vehicle's warm-up time was shortened by 20%, and the charge-sustaining fuel consumption in WLTC cycle can be reduced by 1.3%.

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Definitions/Abbreviations

DM-i - Dual Mode-Intelligent
HT - High Temperature
LT - Low Temperature
1D - One Dimensional
3D - Three Dimensional
DHE - Dedicated Hybrid Engine
TMM - Thermal Management Module
BTE - Brake Thermal Efficiency
OEM - Original Equipment Manufacturer
WP - Water Pump
WJ - Water Jacket
IEM - Integrated Exhaust Manifold
HTC - Heat Transfer Coefficient
WOT - Wide Open Throttle
EGR - Exhaust Gas Recirculation
BSFC - Brake Specific Fuel Consumption
ECU - Engine Control Unit

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