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Research of Control Strategy of Armored Vehicle Cooling System

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Abstract

A cooling system with high and low temperature double circulations was built. On the basis of analysis of cooling demand of the various components of armored vehicles, the control strategy of the cooling system was designed, which were based on presetting MAP and fuzzy control. The Coupling Model of the cooling system and the control system was built in Matlab/Simulink software. The simulation results showed the control strategy was effective. Experiments on cooling system test bench validated the control strategy was workable. The research indicate that the control strategy based on presetting MAP and fuzzy control could satisfy the control demand of high and low temperature double circulations cooling system, which at the same time ensure that the temperature of coolant at the outlet of engine block fluctuate no more than 1K, the temperature of low temperature circulation below the set value.

***Keywords**: Cooling system, Control strategy, Presetting MAP, Fuzzy control.*

1. Introduction

With the increasing of engine power of armored vehicles, which also increased the heat dissipation, the cooling system consumed more power. In traditional armored vehicle cooling systems, fans and pumps were directly driven by diesel engines with fixed speed ratio. Meanwhile the fluctuations of temperature of coolant could easily lead to increased diesel fuel consumption and reduce the reliability of key components, which would impact the lifespan of diesel engine [1-2]. However, due to the speed of fan still directly related to the engine speed, and only limited stalls, the coolant temperature still greater fluctuated.

Intelligent controlled Cooling system, which can adjust the flow rate of coolant and cooling air on demand make the diesel engine work in appropriate conditions within the optimal temperature range, could reduce the power consumption of the cooling system and the fluctuations of coolant temperature, and reduce the thermal fatigue of key components of diesel. Many research has been carried out in many foreign countries [3], while some research on civilian vehicles were also carried out in domestic. Researches have shown that the intelligent controlled cooling system could significantly reduce the power consumption of cooling system [4].

Compared with civilian vehicles, the working conditions of armored vehicles is complicated because of its special operating environment. The cooling system contains multiple thermal components, and each of the various components demands different cooling temperature which needs deep and extensive research.

A one-dimensional model of a type of armored vehicle cooling system have been established in this paper, based on the principle of minimum coolant temperature fluctuations and minimum power consumption, a cooling system control strategy have been developed using fuzzy control combined with presetting MAP, which were tested on cooling system test bench. Experimental results indicated that the control strategy could maintain the coolant temperature stable, and reasonably regulate the speed of fan

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and pump and reduce the consumption of fan and pump.

2. Modeling of Armored Vehicle Cooling System

2.1. The Structure of Armored Vehicle Cooling System

Compared with civilian small vehicle cooling systems, Armored vehicle cooling system has the features that more dissipation power, greater water pump and fan drive power, greater flow rate of cooling medium (cooling air and coolant) and more cooling components. To meet the multiple cooling demands of armored vehicle different components, the cooling system uses a double-loop structure with a high temperature (HT) circulation and low temperature (LT) circulation, as shown in Figure 1, where engine block and first intercooler were parallel arranged in high-temperature circulation, interstate intercooler and second intercooler were series connected in low-temperature circulation. High temperature radiator and low temperature radiator were superposed. Cooling air flowed through the cooling fan, low temperature radiator and high temperature radiator sequentially.

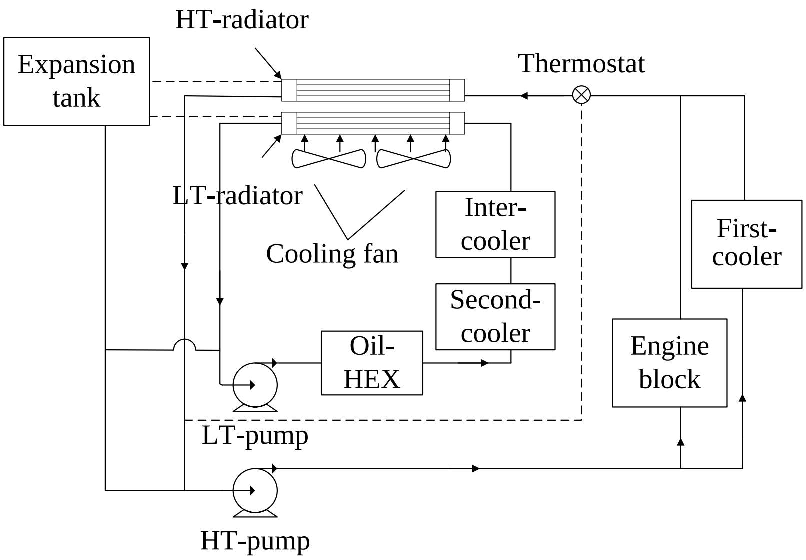

Figure 1. The Cooling System with High and Low Temperature -Double Circulations

2.2. Modeling of the Cooling System with HT and LT Double-Circulation

Using lumped parameter method, taking the quality of the diesel engine and the heat capacity into account, ignoring the impact of the specific structure of the water jacket and the effects of the diesel radiation and convective heat transfer, equations of heat transfer between the diesel engine and cooling system were established as follows[5].

$$Q_w = h_{eng} A_{eng} [T_{eng} - 0.5(T_{w\_out} + T_{w\_in})] \tag{1}$$

$$h_{eng} = 0.027 \mathrm{Re}_w^{0.8} \mathrm{Pr}_w^{1/3} (\frac{\mu_w}{\mu_{eng}})^{0.14} (\frac{\lambda_w}{d_{eng}}) \tag{2}$$

In the Equation (1), T_{eng} was the average temperature of the diesel engine block. M_{eng} was the mass of engine body. C_{eng} was the specific heat of engine water jacket. h_{eng} was the heat transfer coefficient of engine water jacket, which were determined by Equation (2).

After turbocharged the air was cooled after flow through the intercooler. Set the temperature difference of compressed air between the inlet and outlet of intercooler be ΔT_{a-i}. In a certain working condition the intake air mass flow rat was m_a , the volumetric heat capacity of compressed air was $c_{a,v}$, the heat exchange capacity of intercooler was Q_{c-i} , which fit the Equation (3).

$$Q_{c-i} = c_{a,v} m_a \Delta T_{a-i} \tag{3}$$

Let the power of the high temperature pump and the low temperature pump and cooling fan be P_a , $P_{w,h}$, $P_{w,l}$, then:

$$P_a = \frac{H_a Q_a}{\xi_a} \tag{4}$$

$$P_{w,l} = \frac{H_l Q_{w,l}}{\xi_l} \tag{5}$$

$$P_{w,h} = \frac{H_h Q_{w,h}}{\xi_h} \tag{6}$$

Where the subscript a, h and l denote fans, high temperature pump and low temperature pump, H is the pressure, Q is the flow rate. When the pump speed changes, those parameters be recalculated in accordance use the following formula:

$$\frac{n}{n_m} = \frac{Q}{Q_m} = \sqrt{\frac{H}{H_m}} = \sqrt{\frac{p}{p_m}} = \sqrt[3]{\frac{N}{N_m}} \tag{7}$$

According to the heat balance equation, calculate the amount of heat exchange of high temperature radiator and low temperature radiator, the total of low temperature radiator heat exchange:

$$\Phi_l = q_{wl} . \rho_w . c_w . \Delta t_{wl} \tag{8}$$

The total of High-temperature radiator heat exchange:

$$\Phi_h = q_{wh} . \rho_w . c_w . \Delta t_{wh} \tag{9}$$

Where q was the mass flow rate of coolant; c was the specific heat of the coolant; ρ was the density of the coolant, Δt was the temperature difference of coolant between the inlet and outlet of the heat exchanger.

Flow resistance of cooling air and coolant could be calculated according to equation (10).

$$\Delta p = a v^2 \tag{10}$$

Wherein Δp was the flow resistance of the cooling medium, ***a*** was flow resistance coefficients. v was volume flow rate of the cooling medium.

The maximum heat dissipation of thermal components of a certain type of armored were shown in Table 1. According to the structure of cooling system of the armored vehicle and the theory of flow and heat transfer, A model was established in GT-cool, as shown in Figure 2.

Table 1. The Maximal Power of Heat Dissipation of Thermal Parts (Kw)

Parts	Power
Engine Body	315
Middle Cooler	117
First Cooler	126
Second Cooler	126
Oil Cooler	120

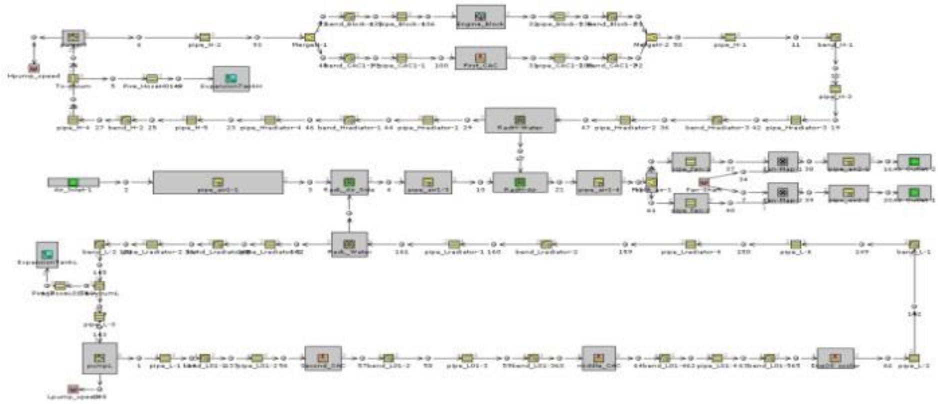

Figure 2. The Model of the Cooling System In GT-Cool

3. Control Strategy of Armored Vehicle Cooling System

Using fuzzy control algorithm combined with presetting MAP, the speed of cooling fan and pumps were controlled to achieve the goal that keeping the temperature of coolant at the outlet of diesel engine stability, at the same time keeping the temperature at the outlet of low-temperature radiator in limited appropriate range.

3.1. Control of Pump Speed

It was found in some researches that when the flow rate of coolant reached to a certain high range, the effect of increasing coolant flow rate of reducing the temperature of coolant was slight[6]. Therefore, presetting MAP was used to the speed of pump in order to simplify the control procedures and improve system responsiveness.

Access to simulation or diesel engine bench, one can get the presetting MAP of speed of high-temperature and low-temperature circulating pumps, the input of which were the engine speed, torque and ambient temperature, the output of which were the speed of high-temperature and low-temperature circulating pump

3.2. Control of Fan Speed

Since the cooling fan was shared by the high-temperature circulation and the low temperature circulation, at the same times for the purpose of improving the responsiveness of the fan, presetting MAP, fuzzy control with feedback of the coolant temperature at the outlet of the diesel engine and conditions control with feedback of the coolant temperature at the outlet of low temperature radiator were adopted to control the speed of fan.

The presetting MAP of the speed of cooling fan can be acquired by the same way of pump.

Fuzzy control is a mature intelligent control method, the advantages of which were that it is not necessary of precise mathematical description of the controlled object. The inputs of fuzzy control MAP were the temperature and the temperature different difference between the output and the target. And the outputs of the MAP were the speed of cooling fan. The approach of Data Storage was used to further eliminate static control error.

The thermal components in low temperature circulation will not occur thermal fatigue, so the circulation is not sensitive to slight fluctuations coolant temperature. Therefore, conditions control was used to the control of coolant temperature of low temperature circulation. The control rules as follows:

Rule 1: if the input temperature is less than 348K, the output is 0；
Rule 2: if the input temperature is less than 351K and higher than 348K, the output is 100;
Rule 3: if the input temperature is less than 353K and higher than 351K, the output is 300;
Rule 4: if the input temperature is higher than 353K, the output is 500.

Put the three parts integrated, one can fulfill the control of the speed of cooling fan.
A coupled model was established in Simulink using the data interface between GT and Simulink software, as shown in Figure 3. In the Coupled model, the temperature of high-temperature cycle at the coolant outlet of diesel engine was set 395K, while the temperature of low temperature cycle at the coolant outlet of radiator was set 348K.

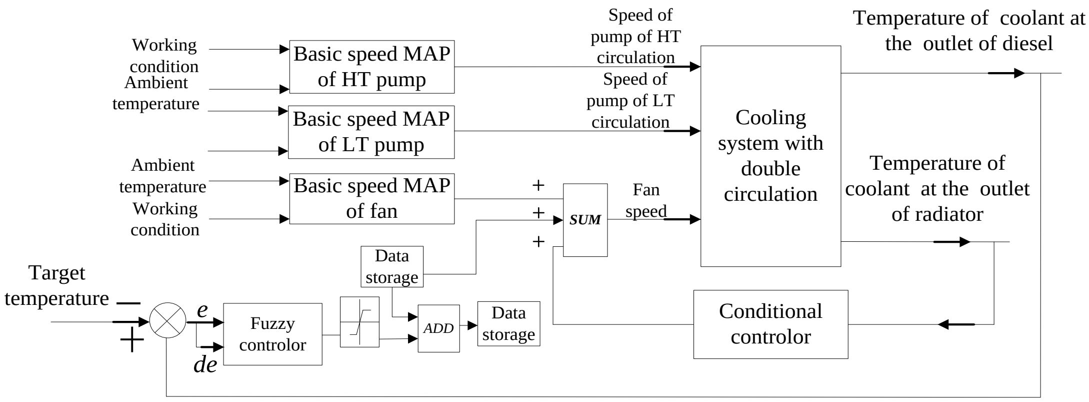

Figure 3. Block Diagram of the Control System

3.3. Simulation and Analysis

Use the cooling system model, and control the speed of pump and fan, making the temperature of the coolant of the two circulations be the target temperature, then one can acquired the presetting MAP of pumps and cooling fan.
The working conditions of Armored vehicles engines were very complex, so three working conditions were set to validate the control strategy which were shown in Table 2.

Table 2. The Set of Working States (Kw)

Parts	1	2	3
Engine Body	155	203	315
Middle Inter Cooler	10	54	117
First Inter Cooler	37	97	126
Second Inter Cooler	34	94	126
Oil Cooler	40	62	120

Using the coupled model of cooling systems and control systems, variable conditions process was simulated, the results of which were shown in Figure 4 to Figure 6.
In variable conditions, simulation conditions were set change as follows: case 2 for the first 0s to 1000s, case 3 for the 1001s to 2000s as, case 1 for the 2001s to the 3000s.
In the process of variable conditions, the temperature of coolant at the outlet of diesel engine fluctuated within a range of ±K.The temperature of coolant at the outlet of the radiator was always below 348K,which met expectations.
Fan speed variety with operating conditions and rapidly changes in the charge of

presetting MAP. After a short, fuzzy controller begins effect. After slowly shaking, the cooling fans run placidity.

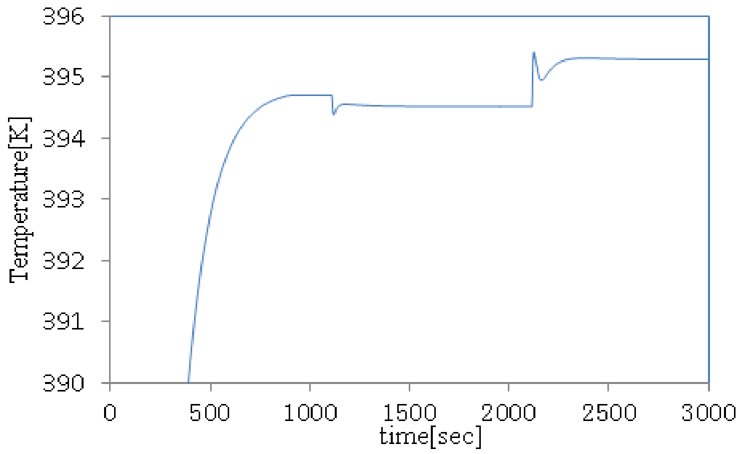

Figure 4. The Temperature of Coolant at the Outlet of Engine Block

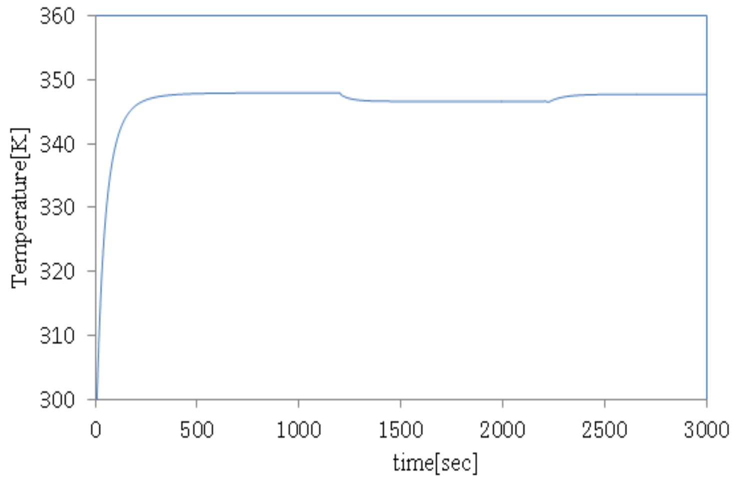

Figure 5. The Temperature of Coolant at The Outlet of Radiator In LT Circulation

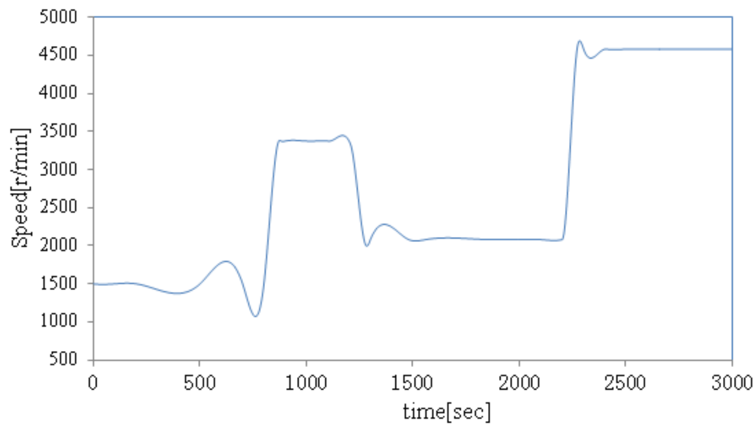

Figure 6. Speed of Cooling Fan

4. Test of Control Strategy on Bench

In order to verify the feasibility of the control strategy, intelligent control tests were taken on the 75kW cooling system test bench. The structure of cooling system test bench was shown in Figure 7, which consists of three parts: condition simulation system (heat source), coolant circulation system and duct. The circulating pump of HT and LT circulation can be controlled. As a result of the high cost of diesel as a heat source with a thermal component cannot be independently controlled amount of heat and other shortcomings. The cooling system test bench was shown in Figure 8. Two of three heat exchangers, arranged in parallel in HT cycle, one heat exchanger arranged in LT cycle to simulate low-temperature components.

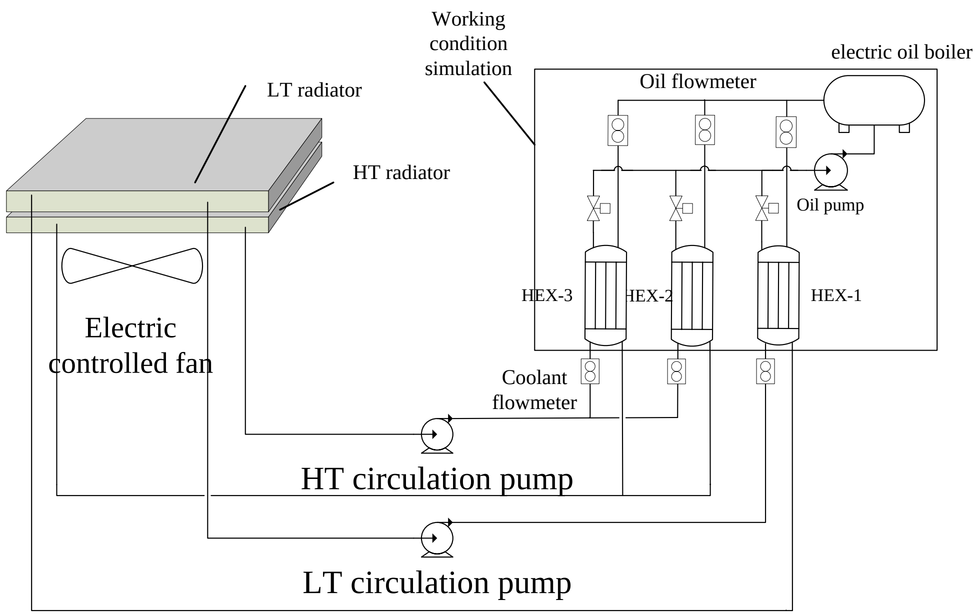

Figure 7. Structure of Cooling System Test Bench

Figure 8. Cooling System Test Bench

Since maximum power of the cooling system test bench using oil boiler was 75kW, it is necessary to reset the power of the three heat exchangers.

Table 3. Set of Working State

Parts	1	2	3
HEX-1	14.5	18.9	7.8
HEX-2	3.5	9.0	19.6
HEX-3	7.8	11.8	33.9

4.1. Acquiring Pumps and Fans Preset MAP

Due to the different between test bench and simulation models, new control MAP of pump and fan were required. After conversion the presetting MAP take directly the power of heat exchanger and an ambient temperature as input， while output the speed of water pump and fan.

4.2. Test of Variable Working Condition

When variable conditions， the test bench conditions were set as follows: case 2 for 0s to 1000s; case 3 for 1001s to 2000s; case1 for 2001s to the 3000s. The temperature of coolant at the outlet of diesel was shown in Figure 9. While the temperature of coolant at the outlet of LT radiator was shown in Figure 10.The speed of fan changes shown in Figure 11.

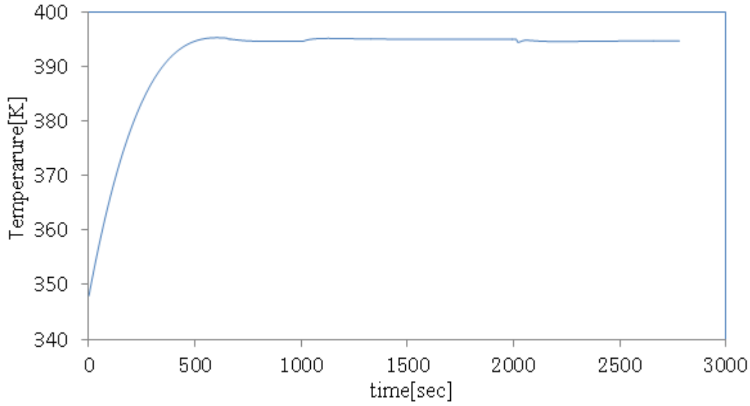

Figure 9. Temperature Changes of Coolant at the Outlet of Engine Block

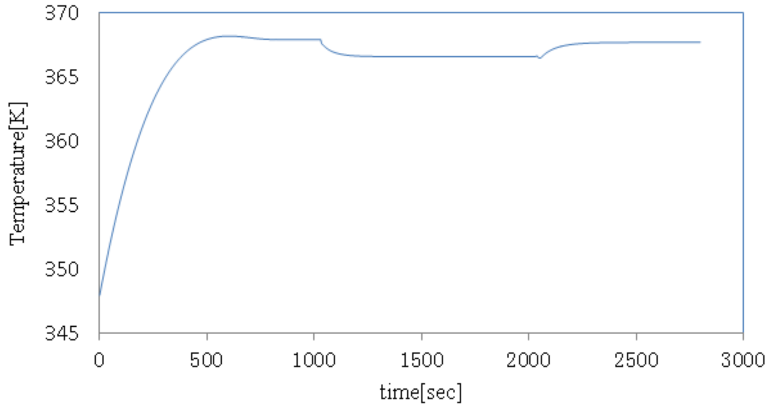

Figure 10. Temperature Changes of Coolant at the Outlet of Radiator in LT Circulation

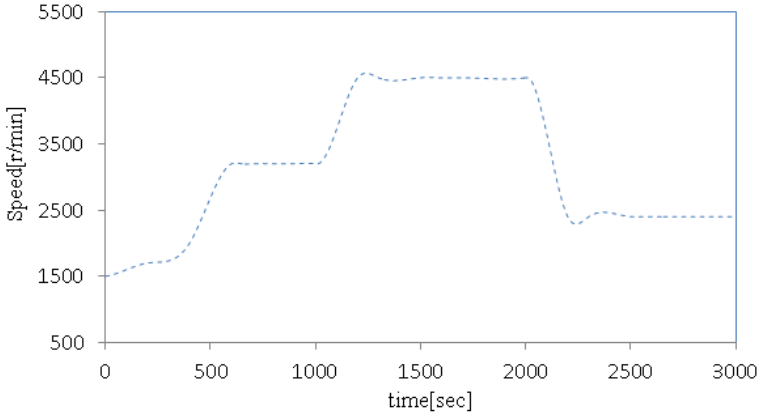

Figure 11. The Speed Changes of Cooling Fan on the Variable Conditions

The temperature of coolant at the outlet of engine shows that when the working conditions changes, the power of heat dissipation increased or decreased， the coolant temperature increased or decreased accordingly. However the magnitude of increase or decrease of temperature was not more than 1K, and become stable speedy at the target temperature. The temperature of coolant in LT circulation was always in control value. The figures of fan and pump speed reflects that the cooling fan and pump change speed closely with the change of working conditions， which provide appropriate cooling， and reduce the consumption of power.

5. Conclusion

(1) Using presetting MAP combined with fuzzy control can achieve effective control on a cooling system with high and low double-loop, the temperature of which at the coolant outlet of engine can be maintained basically stable. The temperature fluctuated no more than 1K in the process of changing working condition.

(2) By bench testing， the control strategy was verified effective in the process of changing working condition.

(3) The Control strategies using a combination of presetting MAP and fuzzy control can adjusted the speed of fan and pumps， which cut down the power consumption of the cooling system.

Acknowledgements

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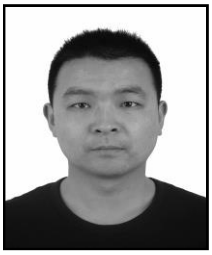

YIN Hong-tao, currently, he is a Ph.D. candidate at School of Academy of Armored Forces Engineering, Beijing China. His research interests include control of vehicle cooling system and vehicle thermal management.

