Global Energy Management for Propulsion, Thermal Management System of a Series-parallel Hybrid Electric Vehicle

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Keywords: Global Energy Management, Dynamic Heat Characteristics, Adaptive Controllable Thermal Management, Coupled Modelling.

Abstract: Energy management in vehicles is a key issue, especially in the case of hybrid electric vehicle. In this paper, a global energy management for propulsion, thermal management system of a series-parallel hybrid electric vehicle is studied. An adaptive controllable thermal management system with two different control strategies suitable for series-parallel hybrid electric vehicle is presented. According to the vehicle structure and schematic, a multi-disciplined coupled model of a series-parallel hybrid electric vehicle combined with propulsion system model and thermal management system model is proposed. The coupled model is explored with the hybrid modelling method which combines experiment modelling and theory modelling. Then the vehicle driving cycle simulations under different cooling control strategies are conducted. Results show that the coupled simulation model can be used to study the energy delivery, distribution and dynamic heat characteristics of propulsion system efficiently. Compared to the traditional on-off cooling control strategy, the power consumption of thermal management system using rule-based cooling control strategy can be decreased by 31.7%.

1 INTRODUCTION

Nowadays, concerns about air pollution and future of energy issues are dramatically increased. In the short term full electric vehicles are prepared to be a substitute to the traditional internal combustion vehicles because of the technology challenges of energy storage system. At present, the hybrid electric vehicle (HEV) is the viable alternative to conventional vehicle. Series-parallel hybrid electric vehicle (SPHEV) is a complex type of HEV, which combines the series and parallel structure with a planetary power split device. With advanced control strategy it can not only take advantage of both series and parallel HEV but also avoid their disadvantages (C. C. Chan, 2002).

With the potential for achieving higher fuel economy, PSHEV has been seen as one of the hybrid powertrain architecture to improve fuel economy when their power-management algorithms are properly designed. Most of the attention has been given to designing energy management control systems in PSHEVs which is responsible to achieve better vehicle fuel efficiency (C. L. Xiang, 2017).

Aside of propulsion, thermal management occupies a significant part of the total energy consumption of the hybrid electric vehicle. Recently, there are a series of research on the thermal management and power distribution of HEV which is presented in depth. Among these, there are some researches considering the effect of thermal management based on different system structures (S. Park, 2008,2010) and different control strategies (F. J. Espadafor, 2015) on whole energy management of series hybrid electric vehicle. The existing energy management strategies of SPHEVs just focus on the improvement of fuel efficiency based on hot engine characteristics neglecting the effect of thermal management system such as temperature on the propulsion system components performance and the vehicle power demand.

In this paper, an adaptive controllable thermal management system suitable for SPHEV is presented. According to the vehicle structure and schematic, a mechanical-electrical-thermal coupled model of a SPHEV combined with propulsion system model and thermal management system

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model is proposed to study the global energy management of the whole vehicle.

2 SCHEMATIC OF SERIES-PARALLEL HYBRID ELECTRIC VEHICLE

2.1 Schematic of Propulsion System

Compared to the others HEV propulsion system, the SPHEV is characterized by multi-range electromechanical transmission belongs to the power split hybrid propulsion system. The schematic of the SPHEV propulsion system is illustrated in Figure 1.

Except for internal combustion engine, there are also two motors in the hybrid propulsion system. These main components are connected by the planetary device. The internal combustion engine is jointed to the planet carrier of the planetary device. The motor A is jointed to the sun gear of the planetary device. The motor B is jointed to the ring of the planetary device which is paralleled with the vehicle output shaft. Considering to the vehicle driving conditions, both the motor A and the motor B can not only operate as a generator but also work as a driving motor. In SPHEV, the engine speed is adjusted by the motor A when it works as a generator according to the work conditions. The power generated by the engine is split by the planetary power coupling device and then formed into different power flow under different driving condition.

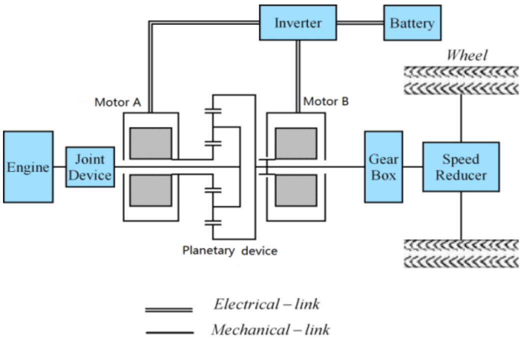


Figure 1: Schematic of series-parallel hybrid electric vehicle propulsion system with planetary device.

2.2 Schematic of Thermal Management System

An adaptive controllable thermal management system suitable for SPHEV is proposed which is shown in Figure 2. It is fully designed on the consideration of the global energy management which not only consider the temperature effect on the propulsion system components but also take into account the effect of thermal management power consuming on the whole vehicle power demand. There are three water circulation loops in the thermal management system. One is high temperature water circulation loop which is used to cool the internal combustion engine. The other two are low temperature water circulation loops which are used to cool the electric motors and their controllers separately. The oil cooler is arranged in the motor low temperature water circulation loop because of transmission oi temperature requirement. Three radiators are integrated into one radiator module. In the air loop, an air stream is inducted through a grille from the top of vehicle which is powered by two electric fans. Then it passes in turn through two low temperature water radiator which is installed in parallel and one high temperature water radiator which is installed with the low temperature radiators in series. Finally, the air stream washes over the powertrain set in the power compartment and be exhausted by the fans through another grille.

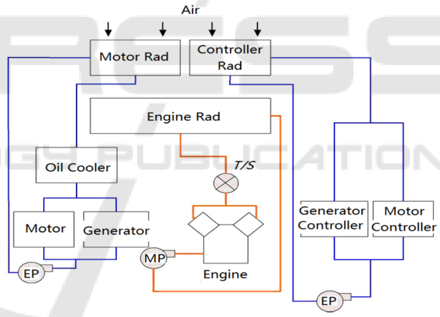


Figure 2: Schematic of series-parallel hybrid electric vehicle thermal management system (Rad: Radiator, EP: Electric Pump, MP: Mechanical Pump, T/S: Thermostat).

3 MULTI-DISCIPLINED COUPLED SIMULATION MODELLING

A mechanical-electrical-thermal coupled model is established by multi-disciplinary hybrid modelling method which can decompose the whole system into several relatively independent subsystems. The large coupling problem can be decomposed into small and easy handling sub-problems. The complex mutual coupled Modelling can be converted into a number of independent subsystem modelling.

3.1 Propulsion System Modelling

This part introduces the models of the components in the vehicle propulsion system. The hybrid modelling method which combines experiment modelling with theory modelling is adopted.

3.1.1 Internal Combustion Engine

Due to the significant nonlinearity of the engine, the real engine model is quite complicated. In this paper, the experimental data are used to obtain the engine performance maps, including the engine's external characteristic map and the engine fuel consumption characteristics map. Then an engine torque output module is used to acquire the engine output torque from a look-up table by the engine throttle signal and the current speed. The engine fuel consumption is calculated by the current engine speed, torque and engine fuel consumption rate.

3.1.2 Motor and Controller System

The experimental modelling method is also used in motors and controllers modelling process, which emphasizes on the input and output characteristics. The characteristic maps of the motors are obtained by the motor bench test. The motor model mainly includes a torque calculation module and a current calculation module. Firstly, the motor receives the target torque command. Then the torque calculation module determines the maximum drive torque in electric operating condition or the maximum braking torque in braking condition which can be used as a constraint of the motor output torque. Motor current calculation module is used to calculate the driving power or the generating power by the motor current output speed, torque and motor efficiency factor acquired from the motor efficiency curve shown in Figure 3.

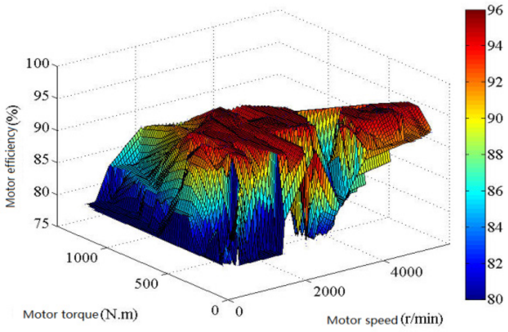


Figure 3: Motor efficiency curve.

3.1.3 Energy Storage System

In the SPHEV, the energy storage system is lithium battery pack. In this paper, the model of the battery pack is modelled by the internal resistance model. The battery pack is modelled as a controllable voltage source and a variable resistor. The equivalent circuit diagram is shown in Figure 4. The battery model outputs the state of charge (SOC) of the battery pack and provides an electrical interface to the generator and the motor.

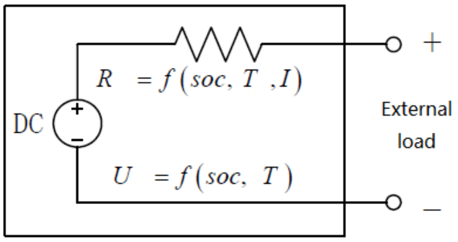


Figure 4: Battery internal resistor model. (R: Battery internal resistor, U: Voltage, soc: state of charge, T: Temperature, I: Current).

3.2 Thermal Management System Modelling

In order to guarantee working performance and reliability of the propulsion system components, an adaptive controllable thermal management system has been used for the propulsion system heat dissipation. On the other side, the thermal management system requires electrical energy to fulfil its duty. Therefore the power consumption of the thermal management system drive components such as electric fan and electric pump need to be considered in the total power demand.

The battery has the integrated cooling system in the battery pack which is not the research focus in this paper. So this part can be neglect in the thermal management system.

3.2.1 Heat Sink Component

Heat sink components are heat exchangers that reject heat to the ambient air. The calculation applies the following formula (Z. P. Yao, 2001).

$$\Phi_a = m_a c_{pa} (t_a'' - t_a') \tag{1}$$

Φ_a is the quantity of heat removed of air side, m_a is the air mass flow, c_{pa} is the specific heat capacity of the air, t_a' is the inlet temperature of air, t_a'' is the outlet temperature of air.

$$\Phi_w = m_w c_{pw}(t_w^{'} - t_w^{''}) \tag{2}$$

Φ_w is the quantity of heat removed of water side, m_w is the mass flow rate of water, c_{pw} is the specific heat capacity of water, $t_w^{'}$ is the inlet temperature of water, $t_w^{''}$ is the outlet temperature of water.

$$\begin{cases} \Phi_s = KA\Delta t_m \\ \Delta t_m = \dfrac{\left(t_a^{'} - t_w^{'}\right) - \left(t_a^{''} - t_w^{''}\right)}{\ln \dfrac{t_a^{'} - t_w^{'}}{t_a^{''} - t_w^{''}}} \end{cases} \tag{3}$$

Φ_s is the quantity of heat removed of radiator, K is the heat transfer coefficient of the radiator, A is the heat transfer area, Δt_m is the difference in temperature between the fluid entering the heat exchanger.

$$\Delta P = f \frac{\rho_a u_a^2}{2} \frac{L}{d_e} \tag{4}$$

ΔP is the air flow pressure drop, f is the air flow resistance coefficient, ρ_a is the air density, u_a is the air velocity, L is the length of flow pipe, d_e is the equivalent diameter.

$$h_f = \frac{0.316}{\mathrm{Re}^{0.25}} \frac{l}{d} \frac{u_c^2}{2g} \tag{5}$$

h_f is the coolant pressure loss of the straight pipe, Re is the Renault number, l is the length of the coolant flow pipe, d is the inside diameter of the pipe, u_c is the coolant velocity, g is the acceleration of gravity.

3.2.2 Electric Fan

The heat dissipation of the internal combustion engine and electrical components is delivered by water and through radiators where it is transferred to air by electric fans. Two electrical fans have been arranged in parallel according to the structure of the thermal management system. The specific performance curve of the electric fan is described in Figure 5.

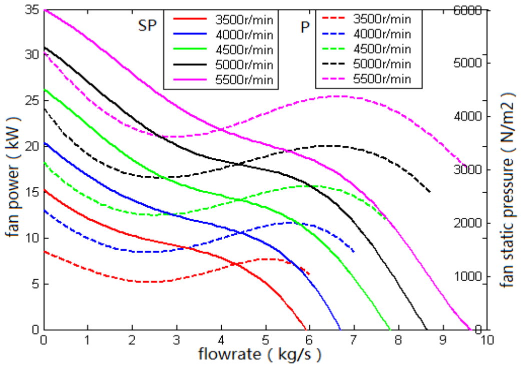


Figure 5: Electric fan performance curve. (SP: static pressure, P: power).

3.2.3 Coolant Pump

There are totally three pumps in the thermal management system. Two electric water pumps are used in the circulation of the motor cooling circuit and controller cooling circuit. One mechanic water pump which is propelled by engine directly is used in the engine cooling circuit. The specific performance curve of the electric pump is described in Figure 6(Francisco, 2015).

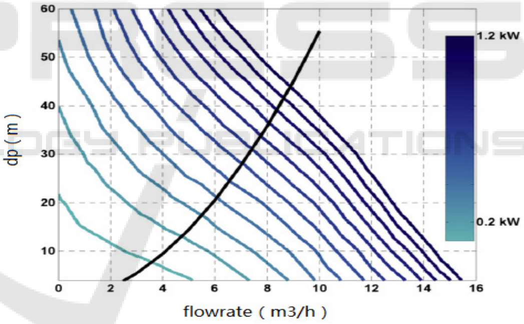


Figure 6: Electric pump performance curve.

4 GLOBAL ENERGY MANAGEMENT STRATEGY FOR SPHEV

The power distribution flexibility of SPHEV brings a more complex energy management problem. The energy management strategy of HEV can be divided into two categories, namely rule-based and optimization-based. Although on some particular occasions driving cycle can be known, it is usually unavailable in some off-road conditions which causes rule-based strategies be the most useful. In this paper a rule-based energy management strategy has been chosen for the SPHEV.

According to the driving condition, the SPHEV can explore a variety of working modes. Vehicle stop mode includes vehicle stopping and stopping & charging conditions. The latter one is a special case of the vehicle stopping mode. Electric driving mode is applied in the low speed and small load condition. Engine single driving mode is applied in the situation that vehicle required torque is in the engine high efficiency load areas. Hybrid driving mode is applied to full load acceleration or climbing conditions. Braking mode includes electrical braking and mechanical braking is applied in brake condition.

For different working modes, the energy management adopts the control strategy based on the power distribution rules. First, the total demand power of the vehicle including the vehicle driving power and auxiliary power is distributed between the engine and the battery, and then the engine power is distributed between the motor A and the mechanical power. On the premise that battery SOC is maintained at optimal working range, engine works in the optimal efficiency range by the adjustment of the battery. Motor A is used to adjust the engine speed into the optimal speed range in order to realize the best fuel consumption.

Under this situation, the speeds of fans and pumps are controlled by the thermal management system which is also considered in the global energy management system. There are two thermal management control strategies are applied in this paper. One is traditional on-off control strategy. The other one is rule-based control strategy which is realized by the rule-based map determined by the different vehicle working modes. Compared to the traditional on-off control, this rule-based cooling control strategy is more elaborate. The specific control target temperatures of propulsion components can be seen in Table 1.

Table 1: The control target temperatures of propulsion components.

Propulsion component	Control target outlet water temperature（K）
Engine	376
Generator	358
Motor	358
Generator controller	338
Motor controller	338

5 RESULTS AND DISCUSSIONS

A series of simulations under UDDS driving cycle using different cooling control strategies are conducted. The international general urban road driving cycle UDDS is shown in Figure 7. In the UDDS driving cycle, the maximum velocity is 91.2 km/h. In the simulation, the initial SOC of the battery is set to 0.8. The vehicle needs to start, stop, accelerate and brake frequently throughout this driving cycle. The total demanding power of SPHEV is shown in Figure 8. The demanding power is distributed between the engine power and the battery power. The engine power over the whole driving cycle can be seen in Figure 9. The histories of battery SOC and power over the driving cycle can be seen in Figure 10. During the driving cycle, the SOC of the battery always declines. In light of recycling energy of the electrical brake, the SOC changing curve goes up and down accordingly which is related to the charge-and-recharge process. Figure 11 shows the engine and electric components temperature histories over the driving cycle under rule-based cooling control strategy. Figure 12 shows the vehicle thermal management system power consumption over the driving cycle under different cooling control strategies.

The simulation results show that the adaptive controllable thermal management system with rule-based control strategy proposed in this research is suitable for the SPHEV, which can satisfy the heat dissipation requirements of the propulsion components under different driving conditions. Under this circumstance, the propulsion components can work effectively in a better temperature range. On the other side, the power consumption of the vehicle thermal management system can be reduced significantly by using the rule-based control strategy. Compared to the traditional on-off control strategy, the power consumption of the thermal management system using rule-based control strategy can be decreased by 31.7%.

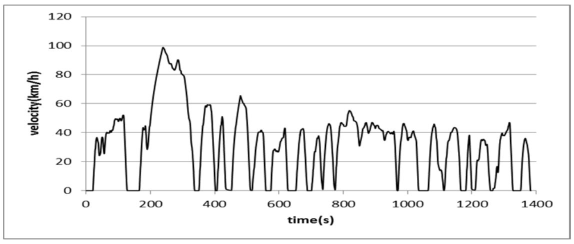


Figure 7: UDDS driving cycle.

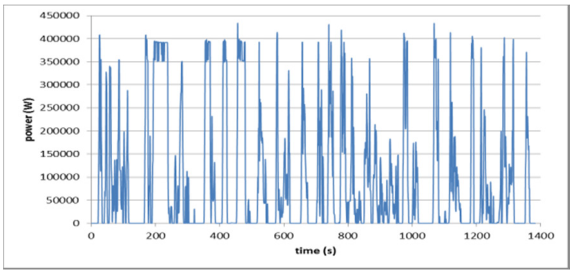


Figure 8: vehicle total demanding power under UDDS driving cycle.

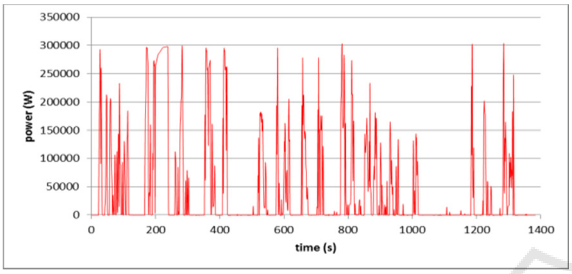


Figure 9: Engine Power under UDDS driving cycle.

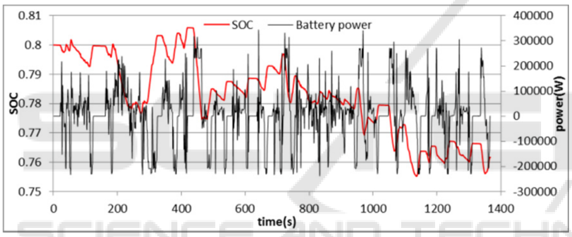
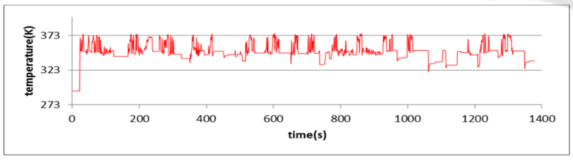
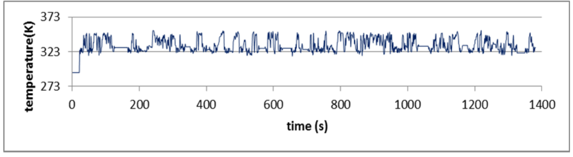


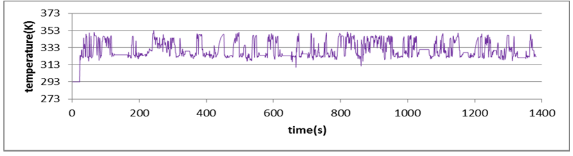
Figure 10: Battery state of charge and power under UDDS driving cycle.



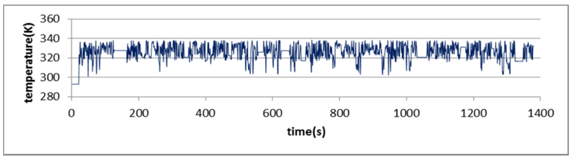
(a) Engine



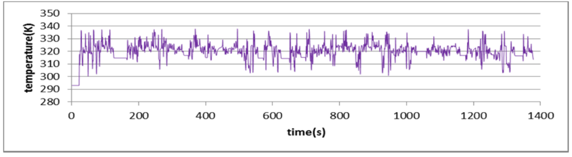
(b) Motor



(c) Generator



(d) Motor controller



(e) Generator controller

Figure 11: Temperature histories of engine and electric components.

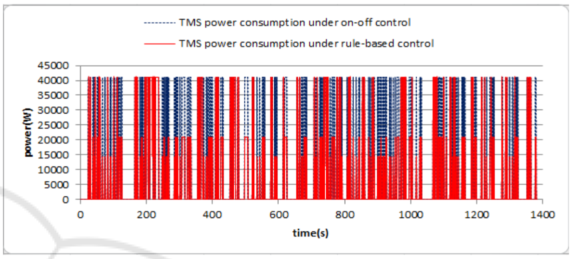


Figure 12: Power consumption of thermal management system under different control strategies. (TMS: thermal management system).

6 CONCLUSIONS

The mechanical-electrical-thermal coupled model established in this paper is very efficient in the power delivery, distribution and dynamic heat response research of SPHEV. With the multi-disciplined coupled model, a global energy management can be realized. The propulsion components heat characteristic and thermal management system power consumption can be synthetically considered. With suitable cooling control strategy, it can not only enhance the propulsion performance, but also reduce the system power consumption.

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