Applied Mechanics and Materials
ISSN: 1662-7482, Vols. 300-301, pp 1022-1026
doi:10.4028/www.scientific.net/AMM.300-301.1022
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Online: 2013-02-13

Research on Heat Transfer Regulation of Power-split Hybrid Electric Vehicle under Silent Watch Operation

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Keywords: Power-split hybrid electric vehicle, heat transfer, silent watch operation.

Abstract. Silent watch operation is a typical driving condition of power-split hybrid electric vehicle (PSHEV) which has advantages of both series and parallel HEVs. Because of the complicated structure and operations of PSHEV, an advanced thermal management system with effective control strategy is needed urgently. Properly-adopted heat transfer regulations under different vehicle driving conditions are the basis of TMS control strategy establishment. In this study, we begin this work from the typical vehicle operation-silent watch operation. Then, the heat transfer regulation of PSHEV under silent watch operation is researched and analyzed with the present advanced TMS. The results can provide theory and data bases for the future research of TMS control strategy for PSHEV.

Introduction

The power-split hybrid electric vehicle (PSHEV) employed in this study is a heavy duty wheeled vehicle. The PSHEV architecture includes components for power generation, energy storage, power split and distribution, energy and power management, thermal management. The PSHEV which is also known as series-parallel hybrids is more beneficial because it has the advantages of both parallel and series types, and their drawbacks can be avoided. The structure of the PSHEV is shown in Fig.1.

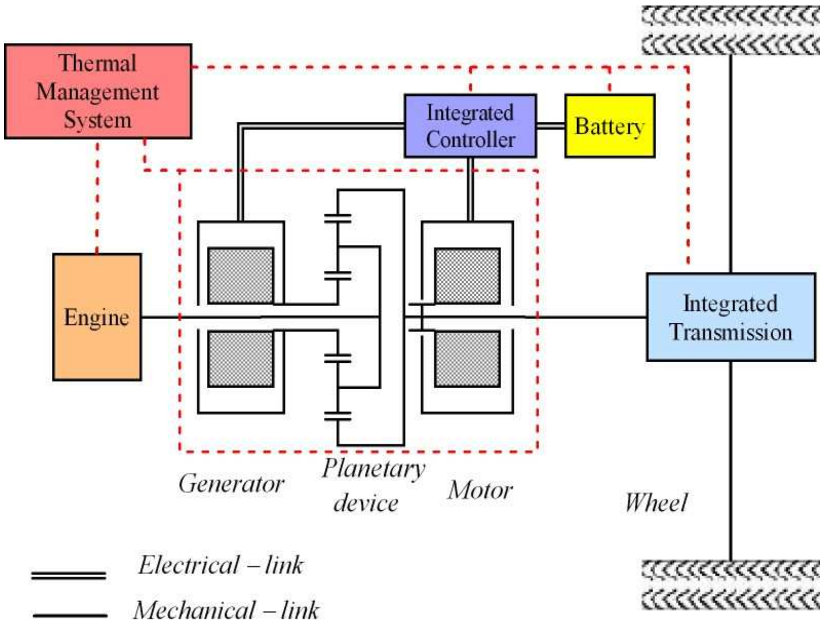

Figure 1. Structure of PSHEV with TMS

The PSHEV energy storage strategy is to use high energy density batteries for absorbing braking energy from the traction motor and for providing burst power for acceleration and thermal management systems. The batteries are also utilized for silent watch operation. Silent watch operation

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is described that the engine is shut off as well as vehicle is driving by the electricity supplying by the batteries. Because of stopping of the engine, the noise and infrared signature are remarkably decreased. So the vehicle's driving safety and cover-up function are increased.

In this study, the PSHEV employs an advanced thermal management system (TMS) which is capable of removing the waste heat generated by the hardware under all operating conditions especially the electric-brake condition[1]. Thermal management of such a complicated energy transfer and utilization system is a major design consideration due to the substantial heat rejection requirements [2-5]. In the present paper, the specific heat transfer regulation for PSHEV under silent watch operation is studied. The influence of different factors (e.g. ambient temperature, velocity, etc.) on the heat transfer is researched.

Silent Watch Operation Trait

Under silent watch operation, PSHEV explores electric driving mode. The power delivery of the vehicle under the situation is shown in Fig. 2. Under this condition, the batteries not only drive the motor to supply the driving power of the vehicle operating, but also supply the electricity powering the assistant system which contains thermal management system. On this circumstance, the thermal load of the vehicle decreases sharply and the power consume of the thermal management system is very small.

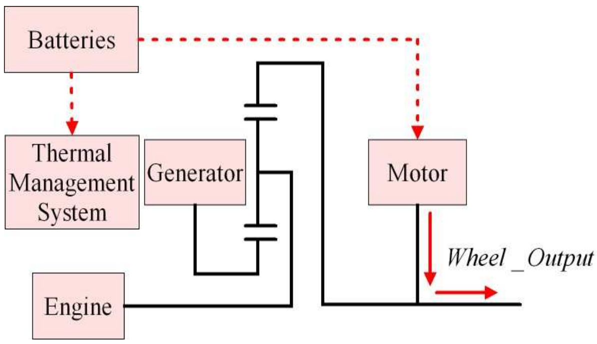

Figure 2. Power distribution of PSHEV under silent watch operation

The heat resource components mainly contain motor, motor controller and transmission oil. Transmission oil and motor are designed in the same cooling circulation in series. Their heat dissipation is circulated by the coolant to the motor radiator. Then the heat dissipation would be expelled to the ambient by a powerful air-stream in the air loop, powered by the electric fans. The heat dissipation of motor controller is expelled by the controller radiator in the same way. The motor radiator and the controller radiator are parallel arranged on the first layer of the radiator module. The schematic of the TMS for PSHEV under silent watch operation is shown in Fig.3.

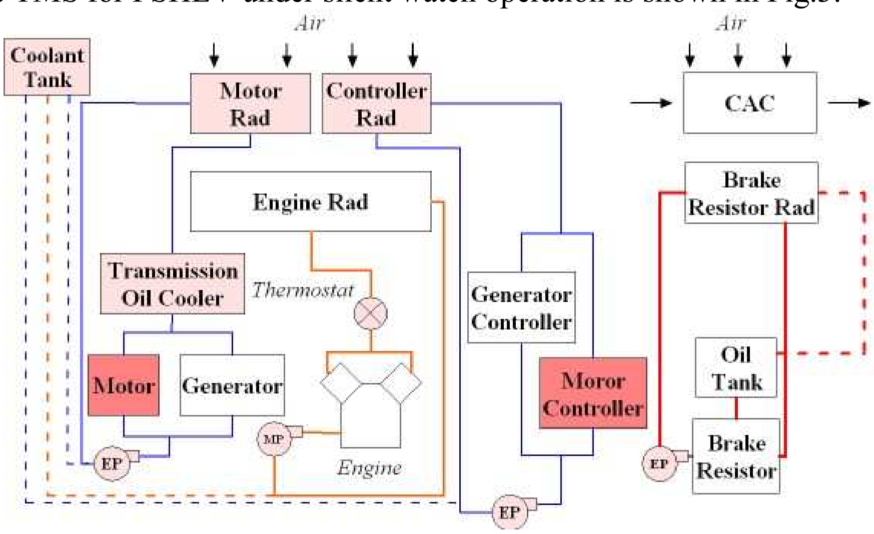

Figure 3. Schematic of TMS for PSHEV under the silent watch operation (Rad: Radiator, EP: Electric Pump, MP: Mechanical Pump, CAC: Charge Air Cooler)

Calculation under Silent Watch Operation

Power Calculation. According to the driving requirement under silent watch operation, the power requirement and the continuous driving distance can be calculated by the following formulas [6].

$$P_{batt\_s} = \frac{V_s}{1000\eta_{ts}}\left(Mgf_r + \frac{1}{2}\rho_a C_D A_f V_s^2\right) \tag{1}$$

V_s is the velocity under silent watch operation, ρ_a is the air density, P_{batt_s} is the power requirement under silent watch operation, M is the mass of PSHEV, g is the acceleration of gravity, f_r is vehicle rolling resistance coefficient, C_D is vehicle air resistance coefficient, A_f is the windard area of the vehicle, η_{ts} is the transmission efficiency from the batteries to the ground under silent watch operation.

$$S = \frac{C_{batt}U_{batt}\Delta SOC\xi(C)V_s}{1000P_{batt\_s}} \tag{2}$$

S is the continuous driving distance which the batteries can supply, C_{batt} is the capacitance of the batteries, U_{batt} is the voltage of the batteries, ΔSOC is the effective charge statement of the batteries, $\xi(C)$ is the temperature influencing coefficient.

The capacitance of the batteries can be calculated by the design requirement of the vehicle continuous driving distance. The actual power of the batteries should fulfill the driving power requirement under silent watch operation at least.

Heat Transfer Calculation. The heat transfer calculation applies the following formulas [7].

$$\Phi_a = m_a c_{pa}(t_a'' - t_a') \tag{3}$$

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

$$\Phi_c = m_c c_{pc}(t_c' - t_c'') \tag{4}$$

Φ_c is the quantity of coolant heat removed, m_c is the mass flow rate of coolant, c_{pc} is the heat capacity of coolant, t_c' is the inlet temperature of coolant, t_c'' is the outlet temperature of coolant.

$$\begin{cases} \Phi_s = KA\Delta t_m \\ \Delta t_m = \dfrac{\left(t_a' - t_c'\right) - \left(t_a'' - t_c''\right)}{\ln \dfrac{t_a' - t_c'}{t_a'' - t_c''}} \end{cases} \tag{5}$$

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

Due to the advantages of cleaning convenience and high pressure endurance, some flat-tube radiator is applied in the TMS. According to abundant experiment data, a correlation of heat transfer coefficient and wind velocity is presented. The heat transfer coefficient varies with the wind velocity and wind resistance. The wind velocity is the main influential factor in the process. The correlation of the heat transfer coefficient and the wind velocity is presented as following[8].

$$K = 88.22e^{0.05265V} - 75.47e^{-0.2328V} \tag{6}$$

K is the heat transfer coefficient of the radiator, $\boldsymbol{V}$ is the wind velocity.

$$\Delta P = f\frac{\rho_a u_a^2}{2}\frac{L}{de} \tag{7}$$

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

$$h_f = \frac{0.316}{\mathrm{Re}^{0.25}}\frac{l}{d}\frac{u_c^2}{2g} \tag{8}$$

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 velocity of the coolant flow.

Under silent watch operation, only motor radiator and controller radiator need to dissipate heat. They are parallel arranged on the first layer in the series-parallel radiator module of the TMS in order to distribute the air mass flow by area.

Results and Discussion

Calculation results show that controller radiator is the limit factor among the whole radiator module under silent watch operation. When the air mass flow supplied by the electric fans is distributed by area, once the air mass flow for the controller radiator is enough, the left air mass flow surely can fulfill the heat dissipation of the motor radiator.

The specific calculation result is shown in Fig.4. When the vehicle velocity is constant, the air mass flow requirement of the TMS increases as the ambient temperature rises. When the ambient temperature fluctuates in the range of 0 ~ 20°C, the air mass flow requirement slightly increases as the ambient temperature rises. It increases more rapidly when the ambient temperature is in the range of 30 ~ 40°C. When the velocity fluctuates in the range of 5 ~ 25km/h, the air mass flow requirement of TMS in summer(40°C) is 28.6~45% larger than that in winter(0°C). When the ambient temperature is constant, the air mass flow requirement will increase with velocity in a very little extent. When the ambient temperature fluctuates from 0°C to 40°C, the air mass flow requirement of TMS at a velocity of 25km/h is about 4.8~18.5% larger than that at a velocity of 5km/h.

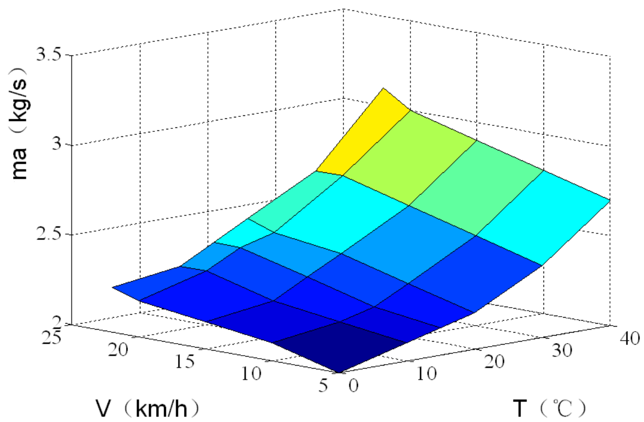

Figure 4. The air mass flow requirement of the radiator module in different velocity and ambient temperature (ma: air mass flow requirement of the radiator module, V: velocity, T: ambient temperature)

The power consumption comparison between the TMS and the whole vehicle in different velocity and ambient temperature is shown in Fig.5. As the increasing of the air mass flow requirement, the power consumptions of the TMS and the whole vehicle increase by linear. When the speed of electric fan is 4000r/min, the air mass flow supplied by two electric fans can fulfill the whole vehicle's heat dissipation under silent watch operation in different ambient temperature and vehicle velocity according to the calculation results. Under silent watch operation, the power consumption of the whole vehicle increases with the rising of velocity by linear. Compared to the whole vehicle's power consumption, the power consumption of the TMS is very small. And the power consumption of the TMS increases with the rising of the ambient temperature and velocity. Because the usual driving velocity under silent watch operation is 15-20km/h, the power consumption of the TMS under this situation is lower than 10W.

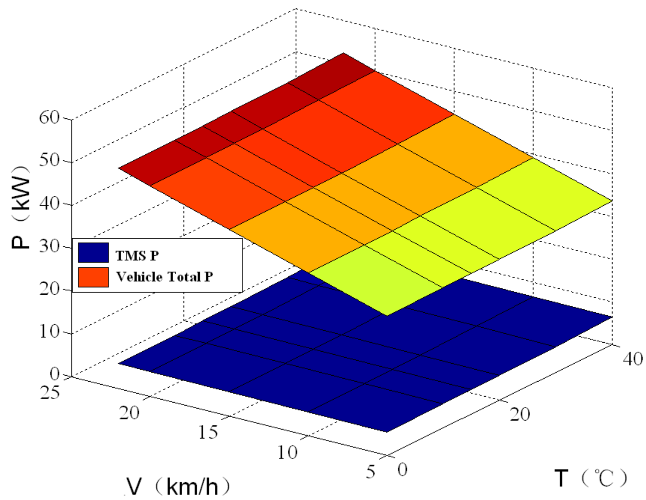

Figure 5. The power consumption comparison between the TMS and the whole vehicle in different velocity and ambient temperature (P: power consumption, V: velocity, T: ambient temperature)

Acknowledgements

Fanatical and technical supports from the China North Vehicle Research Institute and the Beijing Institute of Technology are gratefully acknowledged.

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