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An evaluation of the degree of battery degradation in plug-in hybrid-electric vehicles

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Abstract

A plug-in hybrid-electric vehicle (PHEV) is expected to reduce both the consumption of petroleum and the emission of CO_2 in comparison with ordinary hybrid-electric vehicles (HEV). On the other hand, these advantages strongly depend on the reliability of batteries in PEHVs. Although batteries in PHEVs are used in a harsher condition than those of ordinary HEVs, there are no concrete test methods to evaluate the degradation of the batteries. In this paper, the degree of the battery degradation in a cyclic stress test, which regards to a PHEV model, was investigated and the futures of a substitute test cycle for the regulation was discussed.

Keywords: PHEV (plug in hybrid electric vehicle), lithium battery, state of charge, regulation

1 Introduction

Plug-in hybrid vehicles (PHEV) are expected to emit a lower amount of CO_2 than that of conventional hybrid vehicles. This vehicle uses two different energy sources, petroleum and electricity from a grid. During a short trip, for example 10 to 20 km, this vehicle could be mainly driven by electricity and thus save petroleum. In countries where electricity is generated by low CO_2 emission systems such as nuclear power, the use of this vehicle contributes to a reduction of CO_2 emissions in the whole process of “well to wheel”.

On the other hand, this advantage of a PHEV strongly depends on the lifetime reliability of the PEHV’s battery and the emission of CO_2 will increase as the battery degrades. The distance a PHEV can travel using electrical energy is approximately proportional to the capacity of its battery. Therefore, if the battery’s storage capacity degrades over its lifetime, the PHEV’s electricity-based range will shrink correspondingly. Consequently, the PHEV will begin to require greater engine use and petroleum consumption would increase, even for short trips. Such a reduction of the capacity would cause a higher amount of CO_2 emission because of the use of the engine.

The conditions under which batteries perform in a PHEV are harsher than the use in a conventional HEV because the battery in a PHEV is used in a wider range of states of charge. In a conventional HEV, the battery’s charge can be restored only by the electricity regeneration process during deceleration. Thus, a HEV’s state of charge is continuously depleted and restored within a narrow range. In spite of this, the battery of a PHEV can be charged a higher amount of electricity can be obtained from a grid. Therefore a PHEV’s battery experiences a wider range of states of charge than that of a conventional HEV.

Although a battery in a PHEV must perform under harsher conditions than a conventional HEV, there has no test method developed to evaluate the degradation of a battery in a PHEV. Some reports from the cell phone industry state that the capacity of Li-ion batteries used with a wide range of SOC (State Of Charge) declines after a smaller number of charging and discharging cycles [1]. From this result, it is anticipated that the capacity of batteries in PHEVs will fade much sooner than those in ordinary HEVs. However, battery degradation in PEHVs is rarely reported in the vehicle industry. In addition, only a few papers [2] have proposed test methods to evaluate whether a battery can maintain its initial capacity throughout the lifetime of a PHEV.

This paper will set out details of the experiments and investigation into the capacity degradation of a battery in a test cycle regarding the PHEV model. In addition, a substitute test cycle for a shorter period than the test cycle on account of the regulations will also be discussed.

2 Test method

The degradation in the discharge capacity of a battery in a PHEV, caused by the cyclic stress of electrical charge and discharge, was measured. The cycle consisted of an electrical power variation pattern in a PHEV model, which was a midsized passenger car, when the PHEV was driven with JC08 mode. The electrical power variation pattern in the model PHEV was calculated because no PHEV has been marketed, yet.

2.1 Equations

The electrical power variation pattern of the battery in the PHEV was obtained from the calculation of function (1), which is the function of kinetic energy of a vehicle. The function (1) contained acceleration and a road load. The road load, which is displayed in figure 1, was the function of the speed of the vehicle. The road load referred to that of a conventional hybrid vehicle.

$$\Delta E(t) = (m\alpha + F_r) \times \upsilon(t)\Delta t \tag{1}$$

where ΔE is the kinetic energy of the vehicle in the period of Δt, m is the mass of the vehicle, α is the acceleration, F_r is the road load, υ is the vehicle speed. Acceleration α was calculated by function (2)

$$\alpha = \frac{\Delta \upsilon}{\Delta t} \tag{2}$$

JC08, which is a Japanese standard mode for automobile type approval test in Japan and is displayed in (a) figure 6, was used as a vehicle speed pattern $\upsilon(t)$ in the function (1).

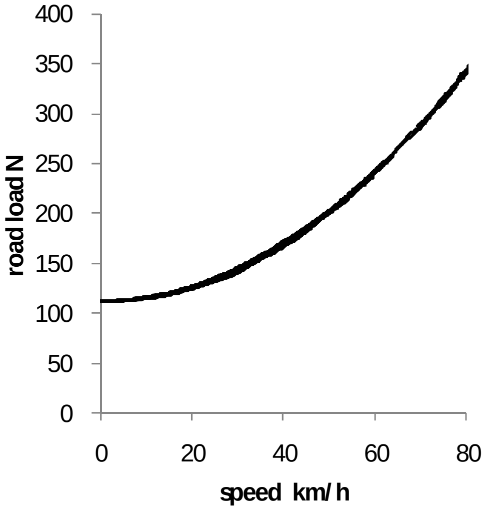

Figure1: Road load of a model vehicle

2.2 Vehicle model

A hypothetical model was used to calculate the power variation pattern of the battery in a PHEV because on PHEVs have been released in the market, yet. The vehicle size is a middle passenger car that has a weight of 1500kg. Figure 1 shows the road load of the model vehicle against the speed.

In addition, four major approximations were used in order to simplify the calculation because the purpose of this paper was not the analysis of a PHEV but the investigation of the battery’s degradation. Firstly, the electrical regeneration during the deceleration of the vehicle is generated proportionally to the torque that follows the decrease of vehicle speed of JC08 in the condition of what the vehicle’s speed was above 15km/h. Secondly, the efficiency of the mechanical power transition from the motor to the wheels though a power train was fixed at 90%. Thirdly, the efficiency of the electrical power transition from the battery to the motor though an inverter was also fixed at 90%. The difference in the calculated current variation from the actual current variation due to these approximations, will be discussed in the next step of this project. Finally, the voltage of the test battery was assumed 180V constant.

2.3 Test battery

A lithium–ion battery was tested in this project because this type of battery has a higher amount of energy density in comparison with other batteries. The comparison of both energy and power densities in several types of batteries is drawn in figure 2. Vehicles have limited spaces to carry batteries in their cabins. Therefore, the batteries that have a higher energy density facilitate a higher amount of energy for propulsion and a longer trip. From this perspective, lithium–ion batteries have a higher potential to be used for PHEVs in comparison with other types of batteries.

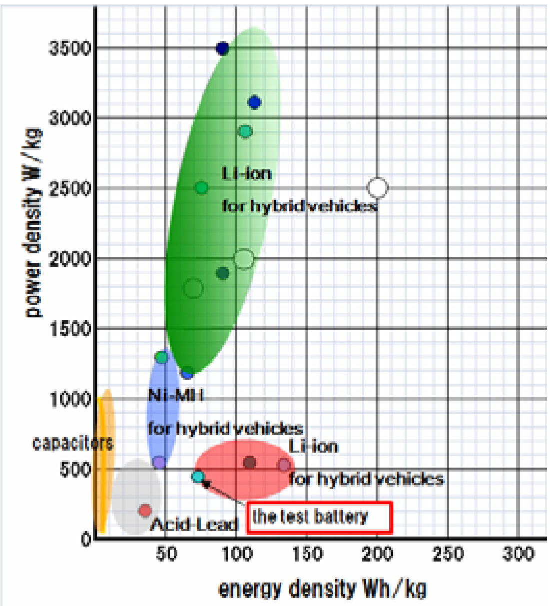

Figure2: power and energy density of batteries for vehicles [3]

A lithium–ion battery that has a negative electrode of LiC_6, was tested in this project because the expansion of the volume of LiC_6 in the process of the charge is smaller than that of other substances. Aforementioned above, batteries in PHEVs are both discharged and charged within a wider range of SOC than that of conventional HEVs. The volume of the surface substance on the negative electrodes in lithium–ion batteries varies in the process of both discharge and charge. The frequent variation of the volume can damage batteries. Figure 3 displays the variation ratio, after charging /before charging, of each substance of the negative electrodes in lithium-ion batteries. It can be seen that LiC_6 with a ratio of 1.1, has a smaller ratio of the volume variation in comparison to other substances in figure 3. Therefore, it was expected that the lithium–ion battery that has a negative electrode of LiC_6 is expected to perform more reliably than other substances. The specification of the test battery module is shown in table 1.

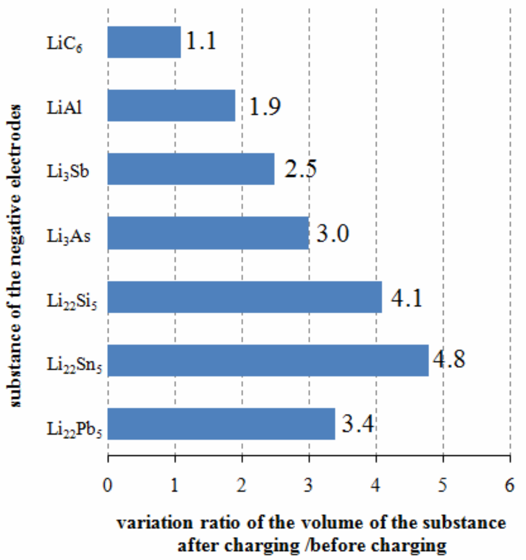

Figure3: variation ratio of the volume of the substances after charge/before charge [4]

Table1: Specification of test battery

manufacture	Licel
type	B4-17-E6MD
capacity	15Ah
number of cells	4ells(serial)
volume	0.36L
weight	0.91kg
energy density	73Wh/kg
power density	470W/kg
naximum current	200A

2.4 Test equipment

The electrical power variation of the test battery was generated by a power supply which can provide maximum/minimum current 700A/-700A. This power supply has a quick rise time of 2ms, such that the current is enough to reproduce the current variation of a battery in a PHEV. The diagram of the connection between the test battery and the power supply is shown in figure 4. The battery was connected to the power supply and was set in a chamber (Espec: WU-200) in order to maintain the temperature of the atmosphere surrounding the test battery during the test period.

The power variation pattern, which is shown in (b) figure 6, was programmed on the power supply by a PC. The data of the test battery, such as cell voltage, current and temperature, was accumulated by the PC though I/O system.

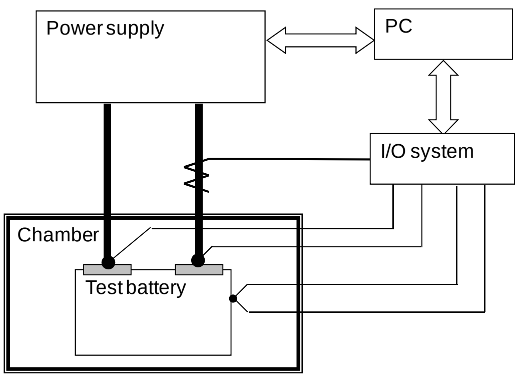

Figure4: Test equipment

2.5 Test condition

The temperature of the atmosphere surrounding the battery was tuned at 25 degrees C in the chamber during the test. 25 degrees C was based on the test condition that JEVS D708 [5] defines as the standard condition for the test of batteries for EV.

On account of a house use of a PHEV, providing a higher amount of electricity only for a PHEV would limit the other uses of electricity. Therefore the electricity of the charge must be limited when the PHEV is charged by the electricity from an outlet of a house. In this experiment, the test cycle was conditioned to draw the degradation of the battery of a house use of a PHEV. Figure 5 displays a 4units of the cyclic stress test. In the period of charge, the test battery was charged in the condition of 0.2C. The average power for the charge with 0.2C becomes 600W/PHEV.

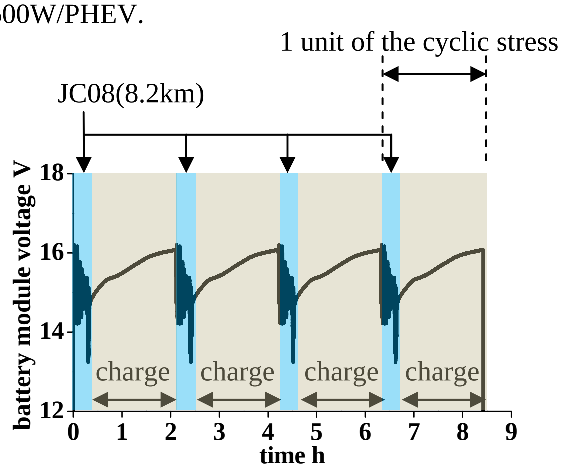

Figure5: 4units of the cyclic stress for the test battery module

3 Calculation

The calculated result of the electrical power variation of a battery in a PHEV is shown in figure 6. Figure 6 (a) displays the variation of the vehicle speed in JC08 mode. Figure 6 (b) is the calculated result of the power variation of the battery in the model PHEV. Figure 6 (c) is also the calculated result of the SOC variation of the battery. In the calculation condition, the start point of SOC was set at 80% as the highest charge condition because the uses of the battery in both the top and the bottom level of the full SOC window is normally avoided in order to protect the battery from its internal destruction.

From the result of this calculation, 816Wh/PHEV of electricity was consumed during the drive of JC08 at one time. The SOC had dropped by approximately 30% through JC08 drive.

The cyclic stress test was applied to the battery with the power variation pattern that was based on this calculation.

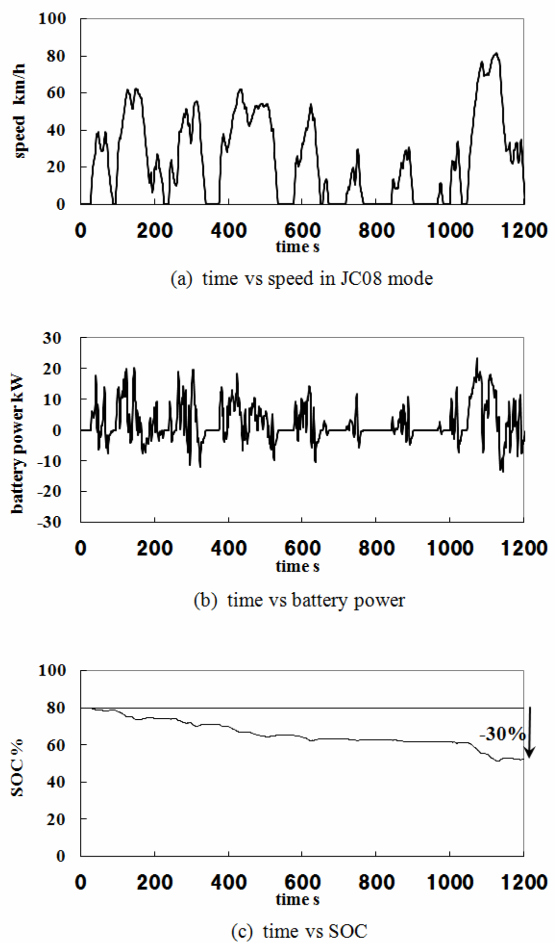

Figure6: calculated result of the electrical power variation of a battery in a PHEV

4 Experimental results

4.1 Decline of discharge capacity

The discharge capacity of the test battery module in a constant current (15A) condition from 16.6V (is assumed as SOC 100%) to 12.0V (is assumed as SOC 0%), was measured every 20 units of the cyclic stress. Figure 7 shows the measured temporal variation of the total voltage of the test battery module in the initial condition, when no stress was yet been applied. The initial discharge capacity was 226Wh.

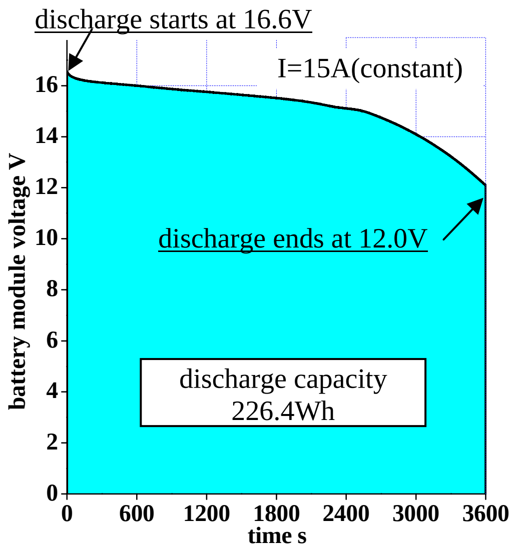

Figure7: initial discharge capacity of the test battery module

Figure 8 shows the decline of the discharge capacity of the test battery module after the application of the cyclic stress. The horizontal scale displays the assumed trip distance that was transformed from the numbers of the units of cyclic stresses. The test battery module has experienced approximately a 1300km trip so far. The decrease of the discharge capacity was -6.6% against that of the initial condition.

A preservation of batteries is another significant factor of the degradation of a battery. Therefore, the effect of the conservation over the degradation of the test battery module was also investigated. Other 2 cells, which are the same type of battery cells with the cells in the test battery module, were also set in the same chamber. These cells were kept in the same environment with the test battery module during the test. The voltages of these cells were kept at 4.0V without the period of the measurement of their capacities. The discharge capacities of these cells were measured simultaneously. Figure 9 shows the discharge capacitances of the cells. The plot of day 64 was correlated to the plot of 1300km in figure 8.

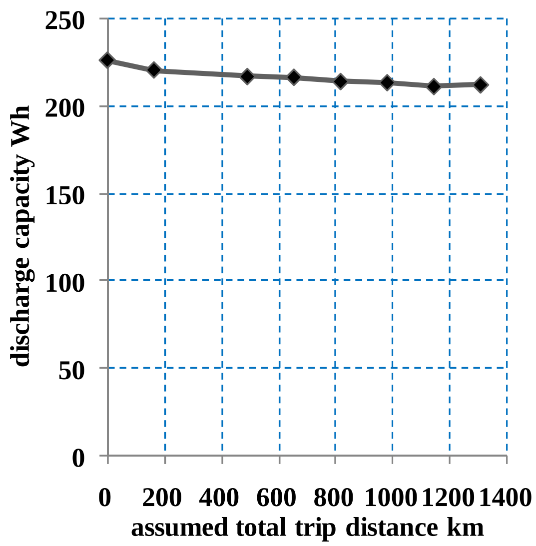

Figure8: decline of the discharge capacity of the test battery module

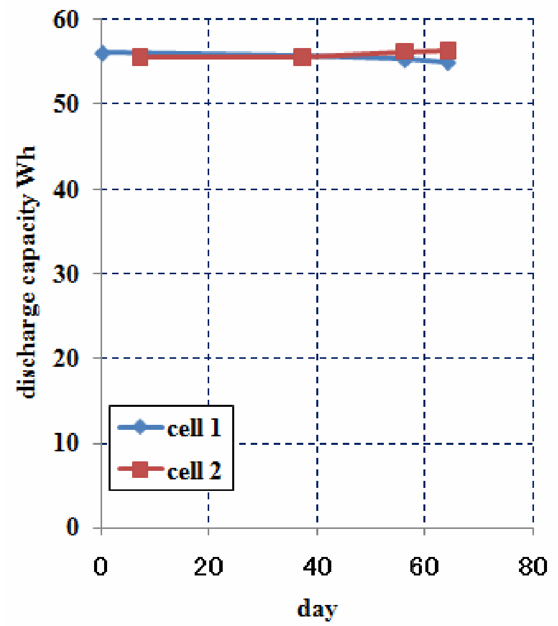

Figure9: discharge capacity of the battery calls without any cyclic stress

From the result of figure 9, no decline of the discharge capacities of these cells was observed in the same period with the cyclic stress test of the test battery module.

5 Discussion

5.1 Influence of preservation

Generally, both electrical stress and preservation affect the degradation of batteries. However, the influence of the preservation was not significant. From the results of figure 8, there was the decline of 6.6% of the discharge capacity. On the other hand, from the result of figure 9, there was no decline by the preservation of the battery cell without any electrical stress. It was clarified that the cyclic stress caused a major decline of the discharge capacity in this experimental condition.

This test cycle will be applied for the test battery in order to observe the degradation, continuously. The small decline, such as 5%, of a discharge capacity in an initial stage of use of lithium ion battery can be observed normally. The characteristic of the degradation of the test battery module by the cyclic stress based on JC08 is expected to be seen with this test method.

5.2 A new pattern of cyclic stress for regulation

Although the cyclic stress of this project was necessary to observe the characteristics of the battery's degradation with JC08, another practical pattern of cyclic stress regarding to the regulation of a test method for car manufacturers is also required. On account of the regulations for car manufacturers, the measurement of the fuel consumption and the CO_2 emission of PHEVs with the batteries that have experienced a long trip are required because these environmental indexes are strongly affected by a degradation of batteries. However, the cyclic stress that was used for this project takes too long time to evaluate these environmental indexes of PHEVs. For instance, in measuring the polluted gases from internal combustion engine vehicles in Japan, testers are regulated to take measurements from vehicles that have experienced the conditions of 80,000km trips [6]. Another appropriate and shorter test pattern should be created for the regulation of PHEVs.

For the establishment of a new cyclic stress, the variation of the current and the heat caused by the current should be considered. The internal resistance of a battery emits heat due to the current and the heat can damage the battery. Therefore, the root mean square value of the current should be taken into account, rather than the average value of the current. The root mean square value current based on JC08 significantly differs from the average value in the same amount of SOC during the charge depletion in JC08. Hypothetically, the average value of the discharge current required to drop the SOC down to 50% from 80% would be 16A with the test battery module. This value is approximately half of the current of root mean square value (35A) during test cycle based on JC08. The new cyclic stress needs to consist of a higher amount of the root mean square value. In addition, the use of a higher amount of the current causes a rapid raise of the temperature of a battery. Therefore, the sub-effect of the use of a higher amount of the current, such as acceleration of the degradation, also needs to be clarified.

6 Conclusion

In conclusion, the initial degradation of the discharge capacity of the test battery module was investigated. It was clarified that the degradation was caused not by the preservation, but by the cyclic stress with the power variation pattern with JC08.

On account of the regulation for PHEVs, some features that a new test cycle should have were discussed. In order to shorten the period of the test cycle, the reduction of charge period would be possible. Furthermore, the sub-effect, such as the acceleration of battery degradation by the use of a higher amount of current, will be investigated in the next step of this project.

Acknowledgments

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References

[1] M. ICHIMUR, *Study of longevity characteristics of small lithium-ion battery*, IEICE technical report, Japan, EE2005-16(2005-07),

[2] H. HIROSE, *Activities for NEDO's project "R&D of fundamental technologies on high performance rechargeable batteries for next generation vehicles*, JARI Research journal, Japan, Vol.30 No.4 (2008)

[3] M. SHIMADA, *Study and Development of a lithium battery that has high durability, capacity and output power*, Proceeding of high performance batteries in the next generation for vehicles (NEDO), Japan, (2008)

[4] K. TATSUMI, *Challenge and vision of battery technologies in the next generation*, Proceeding of summer-time symposium – GIA dialog- JSAE, Japan (2008)

[5] JARI, *Cycle life test procedure of sealed nickel-metal hydride batteries for electric vehicles*, JEVS D708, JARI, Japan (1999)

[6] Road transport bureau, Ministry of land infrastructure transport and tourism, *Legal codes for automotive*, pp.1171-1172, Daiichihoki, Japan (2008)

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