NEW TECHNOLOGIES

Development of High-Performance Lithium-Ion Batteries for Hybrid Electric Vehicles

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Abstract

In view of the need to protect the global environment and save energy, there has been strong demand for the development of electric vehicles (EV) and hybrid electric vehicles (HEV). Aiming at downsizing, weight reduction, improvement of input and output performance as well as the charging/discharging efficiency of batteries, Mitsubishi Motors Corporation has been developing new, high-performance manganese based lithium-ion batteries, suitable for EV and HEV respectively, and proved their excellent performance. This paper introduces the battery mainly for HEV application.

Key words: *Battery, Electric Vehicle, Hybrid Vehicle, Electric Motor, Energy Regeneration*

1. Introduction

To make electric vehicles (EVs) and hybrid electric vehicles (HEVs) viable for general use, manufacturers must increase energy efficiency (and thus reduce fuel consumption and, with regard to HEVs, exhaust emissions) while delivering driving performance and ease of use comparable with those of conventional-engine vehicles. Improvements in propulsion-battery performance are thus crucial(1).

Mitsubishi Motors Corporation (MMC) and Mitsubishi Fuso Truck & Bus Corporation (MFTBC) were quick to identify lithium-ion (Li-ion) batteries as a potential means of meeting these requirements. In conjunction with Japan Storage Battery Co., Ltd., MMC and MFTBC are engaged in development of high-performance manganese-based Li-ion batteries suitable for EVs and HEVs.

Compared with lead-acid batteries and nickel-metal-hydride (Ni-MH) batteries, Li-ion batteries are superior in terms of specific energy (the amount of available energy per unit of mass or volume) and in terms of specific power (the amount of available output per unit of mass or volume). As a result, they are seen as the most promising batteries for secondary-battery applications.

MMC's and MFTBC's involvement in battery development have yielded a number of achievements: A Mitsubishi EV set a Guinness world record by covering more than 2000 km in 24 hours(2), and another completed a 780 km circuit of Shikoku (one of Japan's main islands) with only one charge along the way, further highlighting the growing possibilities of EVs as a means of mobility(3). Also, a Mitsubishi Fuso series-hybrid heavy-duty bus (the first such bus in Japan) has been running successfully on public routes since June 2002. MFTBC has also applied its battery technology to a parallel hybrid propulsion system for the CANTER light-duty truck. This paper describes the superior performance of Li-ion batteries developed for HEVs.

2. Characteristics of Li-ion batteries

Small Li-ion batteries are widely used in mobile telephones, notebook computers, video cameras, and other electronic products owing to their high energy density. Lithium cobalt oxide is used as a positive-electrode material in these small Li-ion batteries. This material has excellent characteristics, but the high price of cobalt makes it too costly for the large batteries used in vehicles. In batteries developed for vehicles, therefore, lithium manganese oxide (a material based on manganese, which is relatively inexpensive and has a limited environmental impact) is used instead. The charging and discharging reactions in a battery of this type are shown in **Fig. 1**.

Manganese-based Li-ion batteries also have the following important characteristics for application to vehicles:

- Their energy efficiency and charging/discharging efficiency are high.
- A high single-cell voltage (three times that of Ni-MH batteries and twice that of lead-acid batteries) means the number of cells in a battery can be relatively small (advantageous with regard to numbers of parts and connections between terminals).
- The state of charge (SOC) can be sensed easily, so charging durations can be managed and driving ranges can be accurately predicted.
- Charging and discharging reactions produce relatively little heat, so a simple cooling system is adequate and operation is possible in a wide range of ambient temperatures.

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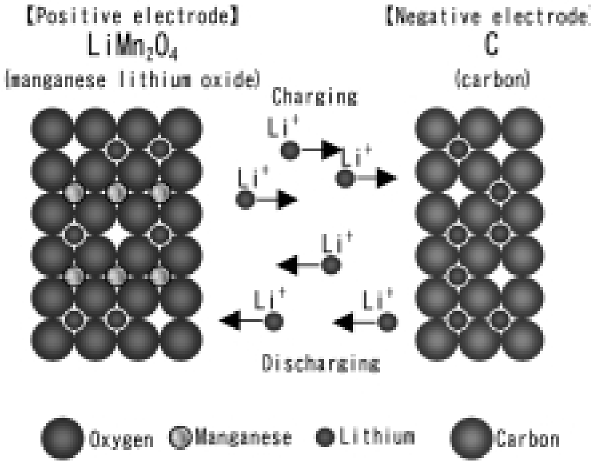

Fig. 1 Schematic of a Li-ion battery

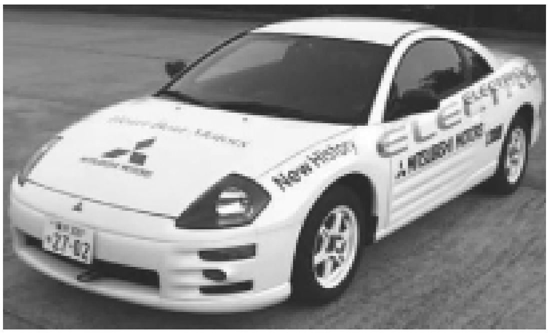

Fig. 2 Mitsubishi ECLIPSE-EV prototype

3. Application to vehicles

3.1 EV batteries

With EV batteries, achieving longer per-charge driving ranges is the primary focus of attention. Since external chargers are needed with EVs, achieving shorter charging durations is also crucial. The LEL80MP battery, which has high specific energy and permits high-current charging, was thus developed. To verify the extent to which the LEL80MP battery could extend total driving ranges by means of longer per-charge driving ranges and shorter charging durations, the battery was fitted in a Mitsubishi FTO-EV prototype and subjected to repeated driving and charging cycles for 24 hours. At the end of the 24-hour period, the vehicle had covered a distance of 2142.3 km, which was recognized as a Guinness world record. Also, a Mitsubishi ECLIPSE-EV prototype (**Fig. 2**) equipped with the LEV95P battery, which has even better capacity and input/output characteristics, completed a 780 km circuit of Shikoku with only one charge along the way, thus indicating a driving range comparable with that of a conventional-engine vehicle. The LEV95P battery's specifications are shown in **Table 1**.

Table 1 Specifications of LEV95P cell

Voltage	(V)	3.75
Capacity	(Ah)	95
Size (W x L x H)	(mm)	94 x 170 x 114
Mass	(kg)	3.5
Specific energy	(Wh/kg)	102
Specific power*	(W/kg)	1060
Specific recharge power*	(W/kg)	280

* : with 50 % SOC after 30 s

3.2 HEV batteries

High output performance is a key requirement of HEV batteries. With a truck, bus, or other heavy-duty HEV, however, large amounts of regenerative braking power make input (charging) performance equally important. The specific power, specific recharge power, specific energy, and battery capacity must be carefully established to match the output required by the motor, the regenerative braking performance, and the hybrid system configuration (series or parallel).

3.2.1 Series HEVs

(1) Overview of AEROSTAR NONSTEP HEV bus

In June 2002, a Mitsubishi Fuso AEROSTAR NONSTEP heavy-duty bus fitted with a series hybrid drive system became the first bus of its kind to enter service on public routes in Japan. A hybrid-series drive system with a diesel-engine generator was adopted for this vehicle. One merit of this system is that it permits the use of compact drivetrain parts and thus gives a high degree of layout freedom, which in turn permits a maximal non-step floor surface (a key requirement for passenger accommodation on a public-service bus). Another reason is that it represents a low-pollution drive arrangement that can be adopted nationwide without new infrastructure facilities. The vehicle in public service is based on one exhibited at the 2000 Tokyo Motor Show. With the Li-ion battery's energy-recovery performance improved and a cooled exhaust-gas recirculation system and an oxidation catalyst added to the engine's intake and exhaust systems, it gives 43 % higher fuel efficiency and 60 % lower nitrogen-oxide emissions than an AEROSTAR NONSTEP bus with a conventional powertrain.

Since only the electric motor is used for propulsion, the battery is subjected to frequent high-current inputs and outputs. Particular importance was thus attached to low internal resistance when the battery was developed. The battery is mounted on the roof of the vehicle. A perspective view of the vehicle is shown in **Fig. 3**, and the vehicle's specifications are shown in **Table 2**.

(2) Battery performance requirements

In establishing the battery specifications, we studied data on actual operation in typical urban situations and determined the battery's required input/output performance in accordance with the required driving and braking forces. Assuming motor efficiency of 90 %, the required battery output power was then calculated as

Table 2 Specifications of AEROSTAR NONSTEP HEV bus

Vehicle			KL-MP37JM (modified)
Capacity (persons)			68
Vehicle dimensions	Overall length	(mm)	10955
	Overall width	(mm)	2490
	Overall height	(mm)	3095
Motor	Type		Induction
	Max. output	(kW)	90 x 2
Generator	Type		Permanent-magnet synchronous
	Max. output	(kW)	40
Engine	Fuel		Diesel fuel
	Displacement	(cc)	8201

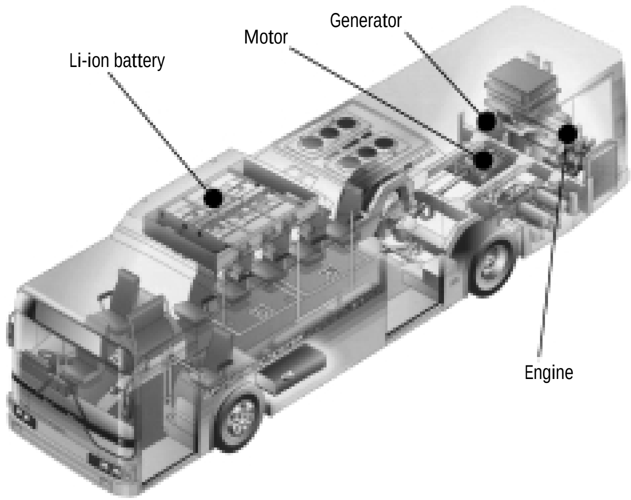

Fig. 3 Perspective view of AEROSTAR NONSTEP HEV bus

Table 3 Specifications of LEC33H and LEC24H

Cell model		LEC33H	LEC24H
Nominal voltage	(V)	3.6	
Capacity	(Ah)	33	24
Size (W x L x H)	(mm)	45 x 109 x 192	
Mass	(kg)	1.9	
Specific energy	(Wh/kg)	62	45
Specific power*	(W/kg)	1440	1580
Specific recharge power*	(W/kg)	460	1000
Number of cells in battery		180	170
Total voltage	(V)	648	612
Total output*	(kW)	450	460
Total input*	(kW)	150	300

* : with 50 % SOC after 10 s

Fig.4 LEC33H and LEC24H single cell

172 kW and the required battery recharge power as 176 kW. To permit recovery of all braking energy (a key factor in the pursuit of high efficiency with the vehicle), a target of at least 176 kW was established for recharge power and output power.

With regard to the total voltage, a 650 V-class motor of the type typically used with streetcars was specified keep the current to a minimum during high-power charging and discharging. The voltage range was set to meet the inverter's requirements.

The battery was mounted on the roof to maximize the non-step floor area, so the battery's mass and size were reduced to the greatest extent permitted by the recharge and output power targets and by the required voltage range.

(3) Battery specifications

In accordance with the aforementioned conditions, the LEC33H Li-ion battery was developed and subjected to various evaluation tests in the AEROSTAR NONSTEP HEV prototype that was exhibited at the 2000 Tokyo Motor Show. The results indicated adequate battery capacity but also showed that a better brake feeling could be achieved if the battery's low-temperature input/output characteristics were improved. The LEC24H battery, an improved version resulting from steps taken to optimize ion conduction for higher input and output capability, was thus adopted for use on public routes. A single cell is shown in **Fig. 4**, and the batteries' specifications are shown in **Table 3**.

In consideration of voltage fluctuations that occur during vehicle acceleration and deceleration and of the required balance of output and capacity, the battery's rated voltage was set at 612 V (rather than the 648 V used with the prototype vehicle). Significantly improved input and output performance made it possible for the propulsion motors to be powered by the battery alone (as with an EV). It was thus possible to significantly reduce exhaust emissions, fuel consumption, and noise and to improve vehicle's dynamic performance.

3.2.2 Parallel HEVs

(1) Overview of CANTER HEV

Series hybrid drive systems are idea for public-service buses, which are driven at relatively low speeds in urban areas. By contrast, parallel hybrid drive systems are suitable for trucks, which are subjected to a wide range of operating conditions. A new parallel hybrid drive system was developed for the popular CANTER light-duty truck, in which it was combined with a small-displacement, low-emission engine and a next-generation mechanical automatic transmission. The result was a highly practical light-duty hybrid truck that realizes low exhaust emissions and low fuel consumption and is easy to drive. The CANTER HEV was exhibited at

Table 4 Specifications of CANTER HEV

Vehicle		CANTER HEV
Dimensions	Overall length (mm)	6235
	Overall width (mm)	1885
	Overall height (mm)	2820
	Wheelbase (mm)	3350
Maximum payload (kg)		2800
Engine		Newly developed low-emission diesel engine
Transmission		Electronically controlled mechanical automatic transmission
Motor	Type	Permanent-magnet synchronous
	Max. output (kW)	35

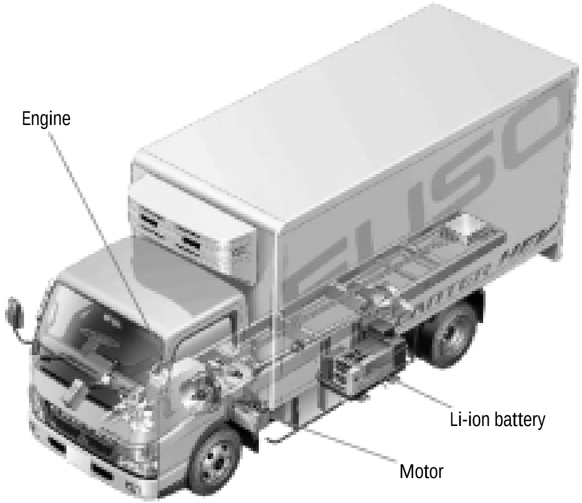

Fig. 5 CANTER HEV

Table 5 Specifications of LEV3H cell

Cell type		LEV3H
Nominal voltage	(V)	3.6
Capacity	(Ah)	3
Size (W x L x H)	(mm)	109 x 19 x 85.5
Mass	(kg)	0.33
Specific energy	(Wh/kg)	33
Specific power*	(W/kg)	2000
Specific recharge power*	(W/kg)	1500
Number of cells in battery		80
Total voltage	(V)	288
Total output*	(kW)	48
Total input*	(kW)	36

* : with 50 % SOC after 10 s

Fig. 6 LEV3H single cell

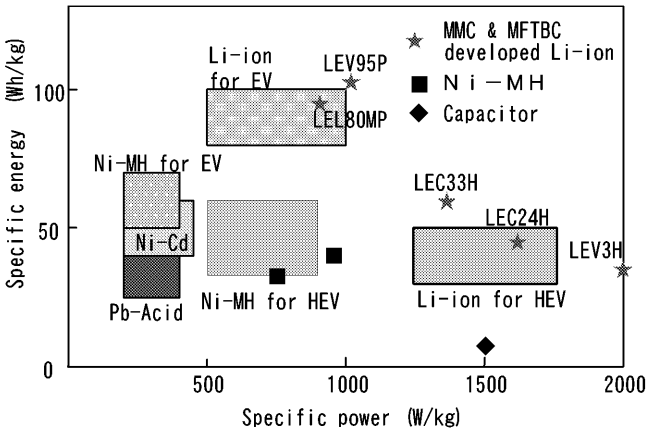

Fig. 7 Relationship between specific power and specific energy

the 2002 Tokyo Motor Show. A perspective view is shown in **Fig. 5**, and major specifications are shown in **Table 4**.

(2) Battery specifications

With a parallel hybrid drive system, the battery is used mainly for engine assistance when the vehicle starts moving and accelerates and for recovery of braking energy when the vehicle decelerates. With a relatively small vehicle, high charge/discharge performance is thus more important than battery capacity. With a truck, however, the higher vehicle weight means that quantities of charge/discharge energy are relatively large, so battery capacity is also crucial. Consequently, the LEV3H battery, which has the high specific energy of a Li-ion battery (and thus exploits the motor's performance potential) and at the same time has a good balance of weight and capacity, was adopted for the parallel hybrid drive system. A single cell is shown in **Fig. 6**, and the battery's specifications are shown in **Table 5**.

4. Test results

4.1 Specific power and specific energy

The relationship between specific power and specific energy for each of the Li-ion batteries mentioned in the preceding section is shown in **Fig. 7**[(4)(5)]. As shown, the newly developed Li-ion batteries each offer good performance (those for EVs having high capacity and those for HEVs having high output).

4.2 Durability

For verification of battery durability, charge/discharge patterns that simulate driving conditions involving harsh acceleration and deceleration are employed in ongoing bench tests. Results for a LEC24H cell are shown in **Fig. 8**. Even after testing equivalent to 300000 km of operation in an actual vehicle, this cell

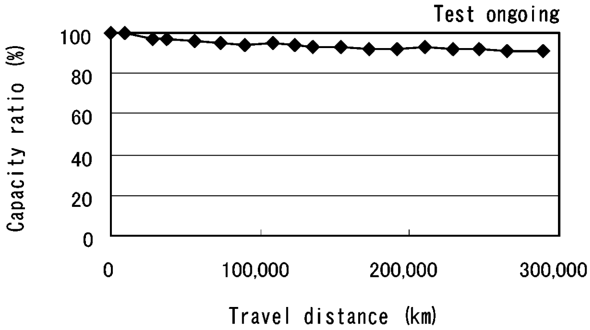

Fig. 8 Results of bench test

Table 6 Abuse test item (single cell)

Item	Details
External short circuit	Wire with resistance of 0.5 mΩ is connected between positive and negative terminals for at least six hours.
Excessive discharging	Cell is discharged to 250 % of rated capacity.
Excessive charging	Cell is charged to 250 % of rated capacity.
Nail penetration	Nail with diameter of 5 mm is driven into center of cell at right angles and left for at least six hours.
Vibration	Cell is subjected to vibration test compliant with JIS D 1601 standard.

retains adequate capacity, thus indicating adequate durability. Questions remain over the appropriateness of estimating deterioration from discharge capacity with batteries used in HEVs, so a method for estimating deterioration with reference to charge/discharge performance is under development.

4.3 Safety and reliability

To prevent a Li-ion battery from deteriorating, the cell voltages must be managed such that the battery is neither excessively discharged nor excessively charged. Consequently, each battery unit is equipped with a control unit that transmits battery-status data and battery-failure data (determined from cell voltages, cell temperatures, and other factors) to a vehicle controller via a controller area network communication system. To enable efficient battery utilization, the control unit incorporates a cell balancer that corrects voltage differences between cells. It also controls a cooling fan mounted on each battery module.

Further, the ability to withstand the abuse items listed in **Table 6** is confirmed to ensure that the battery does not catch fire or cause any other hazard even if it becomes excessively charged or discharged in the event of a control-system fault or becomes damaged in the event of a collision. Evaluation is conducted with a 100 % SOC at room temperature.

5. Summary

The superior characteristics of Li-ion batteries were verified through achievement of EV driving ranges comparable with those of conventional-engine vehicles and through adoption of Li-ion batteries in the AEROSTAR NONSTEP HEV and CANTER HEV.

Battery characteristics significantly influence vehicle performance. With EVs, high-performance Li-ion batteries are essential for longer per-charge driving ranges. And with HEVs, they are a vital means of increasing charging and discharging efficiency, reducing fuel consumption and exhaust emissions, and eliminating the need for external charging (thus enabling easy maintenance).

With the Li-ion batteries described in this paper, MMC and MFTBC not only achieved high performance but also achieved cost savings by using a positive-electrode material based on manganese, which is inexpensive and exists in abundance.

Bearing in mind the need for an optimal balance of battery performance, battery durability, and control-system functionality, MMC will continue working with Japan Storage Battery Co., Ltd. to develop higher-performance batteries and to promote their widespread adoption.

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