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Development of contact-wireless type railcar by lithium ion battery

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1. Introduction

As energy-saving and global warming countermeasures, the use of new energy systems such as rechargeable batteries, fuel cells and super capacitor that reduce carbon dioxide discharge are expected. The transportation section in particular occupies 24% of energy consumption and also 20% of carbon dioxide discharge. So far, lead and nickel hydrogen batteries have been used for hybrid electric vehicles (HEVs) and electric cars or vehicles (EVs). However, these batteries are characterized by low power density and low energy density and are very heavy. Among the rechargeable batteries, lithium ion batteries have the highest energy density and power density and are also the lightest. Therefore, the lithium ion battery is suitable as a power source of certain forms of transportation, including the EV, electric bus and railway. However, Co type lithium ion battery is not suitable because of high cost, low thermal stability, toxicity. Mn type lithium ion battery overcame the demerit of Co type lithium ion battery. Therefore, Mn type lithium ion battery is the mainstream of EV and HEV.

Recently, the rechargeable battery (lithium ion or nickel hydrogen) and fuel cell have been applied on the running of contact-wireless type of railcar (Sameshima, et.al, 2004, Ogasa, et.al, 2006). Lithium ion battery is expected as the driving source of it because of highest energy density and power density among the rechargeable. Some following advantages of contact-wireless type railcar with lithium ion batteries are expected.

(1) The townscape is improved and the maintenance cost of overhead contact wire is reduced.

(2) It is possible to utilize as an emergency power source in the overhead contact wire supply failure by disaster and accident.

(3) The discharge of carbon dioxide, nitrogen oxides and sulhur oxides can be drastically reduced compared with diesel car.

(4) The energy-saving effect for running of railcar is improved by charging regenerative energy with rechargeable batteries.

We have been tried the running test of DC 600V and VVVF (Variable Voltage Variable Frequency) inverter type railcar by using large Mn type lithium ion battery at the business line of local railway (Ozawa, et.al, 2007, 2008) in Japan.

Now, new VVVF inverter type railcars use the regenerative brake which the kinetic energy of railcar converts to electricity that is fed back into contact-wire. However, the regenerative braking loses its effectiveness when there are no other railcars running nearby that railcar immediately use the regenerated electricity. VVVF inverter has been used in the new railcar to raise the energy saving in the running. It was well-known that the loss of regenerative energy often occurred because the regenerative energy was not charged to other railcar which ran nearby. To solve the problem, it is considered that the use of lithium ion battery is effective for the charge of regenerative energy. In this chapter, the performance and energy-saving effect of a railcar which is run by a large Mn type lithium ion battery is described.

2. Lithium ion battery

Homogeneous Al (5mol%) doped lithium manganate powders (LMP) were used as cathode materials. LMP were continuously large produced by spray pyrolysis technique (The flame type spray pyrolysis equipment) using the aqueous solution of lithium nitrate and manganese nitrate (Mukoyama, et.al, 2007). Powder preparation by spray pyrolysis potentially offers the following advantages. (1) The obtained cathode particles are spheres of submicrometer size with a narrow size distribution and have porous microstructure.
(2) Chemical homogeneity of cathode materials is enhanced as compared with those prepared with solid state reaction.
(3) The cathode precursors can be prepared in much shorter time than that required for solid state reaction or the sol-gel method.
Figure 1 show the flame type spray pyrolysis equipment used. It is consisted of two-fluid nozzle, flame furnace with gas burner and powder collector with bag filter. The starting aqueous solution was atomized by a two-fluid nozzle with diameter of 20μm (a) and introduced to flame furnace, in which the temperature of flame was set to 700°C (b). The flame was generated by gas burner with city-gas. LMP was continuously collected with a bag filter (c). Few hundred kg of aluminium doped LMP was successfully produced. It was known that the addition of aluminium ion led to the high stability of life cycle of lithium manganate cathode and avoid the dissolution of manganese ion from LMP. The optimum concentration of aluminium ion was 5mol% from the past experimental results.

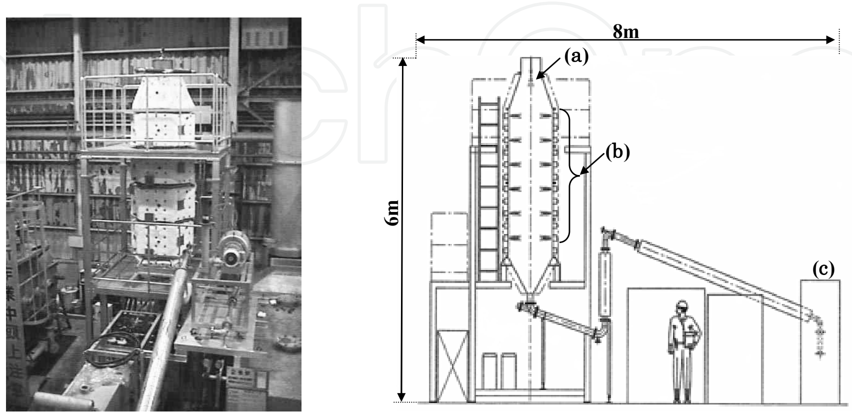

Fig. 1. Flame type spray pyrolysis apparatus

Typical SEM photograph and X-ray diffraction pattern of LMP is shown in Fig.2. SEM photograph showed that LMP had the spherical morphology with non-aggregation and consisted of primary particles with about 100nm. The average particle size and geometrical standard deviation of LMP was about 2μm and 1.3, respectively. Specific surface area of LMP measured by BET method was about $10m^2/g$. X-ray diffraction patterns showed that LMP was well crystallized to spinel structure with a space group (Fd3m). The diffraction lines of impurities except for spinel phase were not observed. Atomic absorption spectrometry analysis showed that the molar ratio of Li/Mn was kept to starting solution composition. The content of aluminium was 4.9mol%.
The electrochemical properties of LMP were investigated using 2032 type coin cell. LMP was well calcined for 12h at 800°C before the use of cathode. It is necessary for use of LMP to reduce the specific surface area to less than $1m^2/g$ because the crack or lamination often occur on the surface of cathode. The cathode was prepared using 88wt% LMP, 6wt% acetylene black and 6wt% fluorine resin (PVDF). LMP was mixed with acetylene black and a fluorine resin to obtain slurry and then coated on an aluminum sheet using a doctor blade. Lithium metal sheet was used as the anode. A porous polypropylene sheet (Cellgard 2400) was used as the separator. As the electrolyte, $1mol/dm^3$ $LiPF_6$ in ethylene carbonate / 1,2-dimethoxyethane (EC : DME = 1:1 in volume ratio) was used. The rechargeable properties of lithium manganate cathode were examined with 2032 type coin cell.
Figure 3 shows the typical rechargeable curves of lithium manganate cathode at rate 1C ($1mA/cm^2$) and the cycle performance at rate of 10C ($10mA/cm^2$). The addition of aluminium ion led to S type of rechargeable curve and the voltage jump which is observed in the rechargeable of lithium manganate at about 4V is disappeared. This suggests that the electrochemical reaction is a homogeneous solid state reaction and the cycle stability of lithium manganate cathode is improved. The first discharge capacity of lithium manganate cathode was 120mAh/g at rate of 1C. The discharge capacity of lithium manganate cathode was retained at about 110mAh/g after 1000th cycle. When the rechargeable rate increased to 10C, the rechargeable capacity decreased to 90mAh/g. However, 90% of first discharge capacity was retained after the 1000th cycle at rate of 10C. It was found that lithium manganate cathode also exhibited high cycle stability at a high rate.

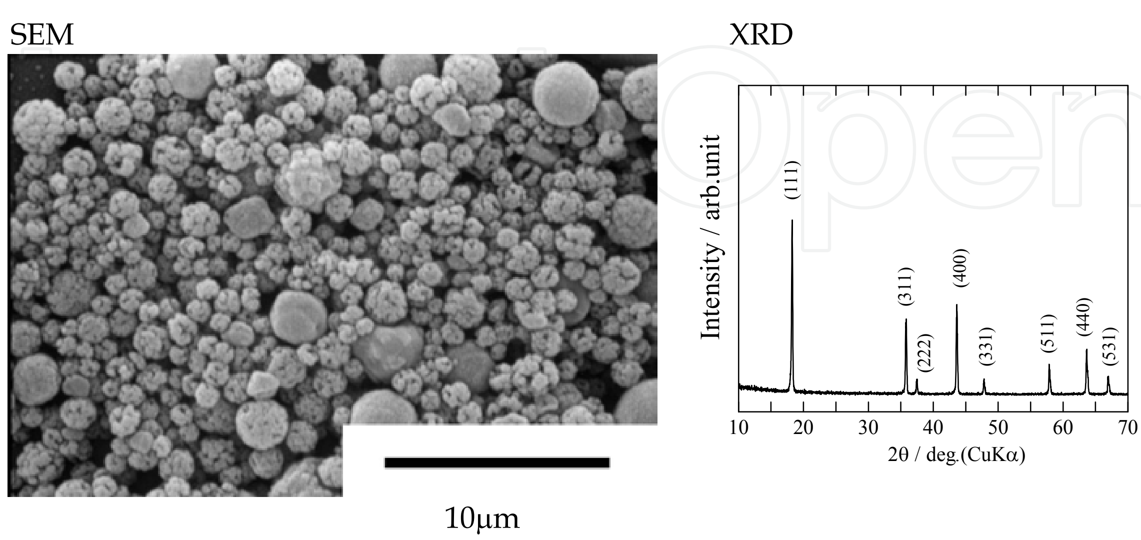

Fig. 2. SEM photograph and XRD patterrn of LMP

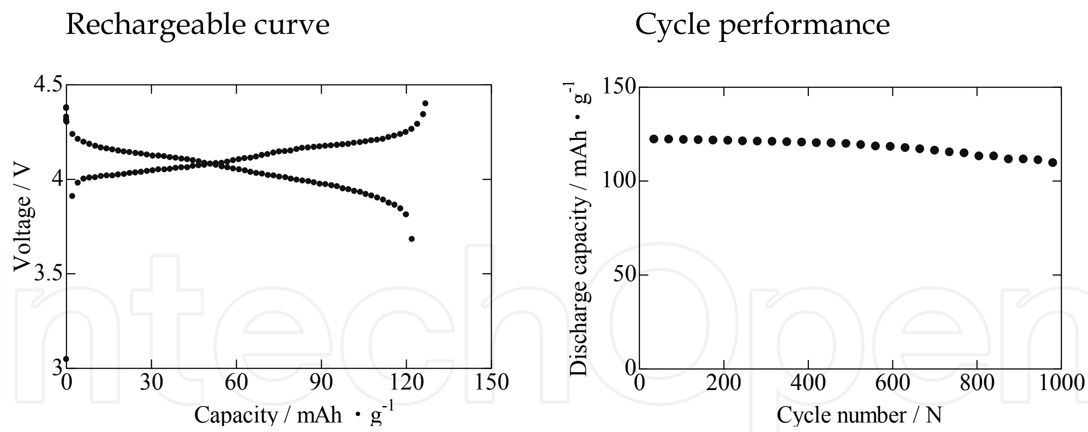

Fig. 3. Rechargeable curve and cycle performance of cathode

A laminate sheet type lithium ion cells (170mm x 160mm x 5mm, 250g, 7Ah, 3.8V) were produced using LMP and a mixture of hard carbon and graphite (volume ratio was 1:1) in a glove box under an argon atmosphere. The rechargeable capacity of laminate sheet type lithium ion cell was 110mAh/g at rate of 1C. The rechargeable capacity of LMP synthesized by classic solid state reaction was about 90mAh/g. The use of LMP derived from spray pyrolysis improved 22% of rechargeable capacity. This result led to high energy and power density of lithium ion cell. The energy and power densities of the lithium ion cell were about 120Wh/kg and 4500W/kg, respectively. The power density was obtained as follows. The voltage in the 10s of applying pulsed current for 10s to 1C was plotted for the current value and power density at state of charge (SOC) 50% was obtained from the linear relationship. This may be resulted in nanostructure of LMP. The charge and discharge among cathode and anode is carried out by fast diffusion rate of Li ion.

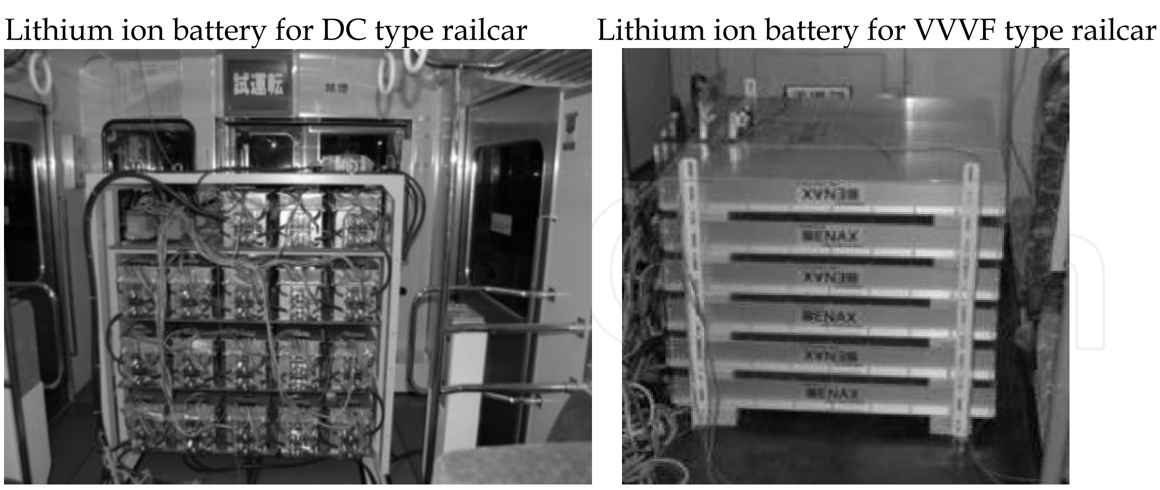

Fig. 4. Lithium ion battery module for railcar

Figure 4 shows large lithium ion battery module for DC type railcar and VVVF type railcar. Lithium ion battery module was consisted of 18 submodules. The submodule (200mm × 150mm × 700mm, 30kg, 84Ah, 34.2V) was made for DC type railcar. Laminate sheet cells which were connected in 9 series were connected in 12 parallels. The aluminium case was used to release a heat from the laminate sheet cell during the charge and discharge. Figure 5 shows the protection circuit and battery management system (BMS). The protection circuits and BMS were installed in all submodules to avoid the overcharge and overdischarge because the high safety must be kept during the running. The change of voltage in all cells was monitored by BMS and then the balance of voltage was adjusted. 18 submodules were connected in series to obtain 45kWh (84Ah, 615.6V) of lithium ion battery module with a weight of 540kg. The submodule (200mm × 50mm × 700mm, 10kg, 28Ah, 34.2V) was consisted of 36 laminate sheet cells for VVVF type railcar. Laminate sheet cells which were connected in 9 series were connected in 4 parallels. Similarly, the aluminium case was used to release a heat from the laminate sheet cells and the protection circuits were installed in all submodules. 18 submodules were connected in series to obtain 15kWh (28Ah, 615.6V) of lithium ion battery module with a weight of 180kg.

Fig. 5. BMS for lithium ion battery

3. Contact-wireless type railcar

3.1 DC type railcar

Various types of DC 600V type railcars (Echizen railway, Japan) with mechanical breaking system were used. Figure 6 (a) shows DC 600V type railcars with weight of 40t used in the running test. Lithium ion battery module was installed in the centre or front of the railcar and fixed in the exclusive rack in order to stand the vibration during the running. 45kWh and 60kWh of lithium ion battery module were used. Lithium ion battery module was directly connected with the motor of the railcar.

DC type railcar VVVF type railcar

Fig. 6. DC and VVVF type Railcar used for running test

3.2 VVVF type railcar

VVVF type railcar (Fukui railway, Japan) with the weight of 25t was used to examine the regenerative effect by lithium ion battery. Figure 6 (b) shows VVVF 600V type railcar with both regenerative breaking and mechanical breaking system. The regenerative breaking action changes to mechanical breaking at 40km/hr. 15 kWh of lithium ion battery module was installed in the front of the railcar and fixed in the wooden rack. Lithium ion battery module was connected with the inverter of the railcar.

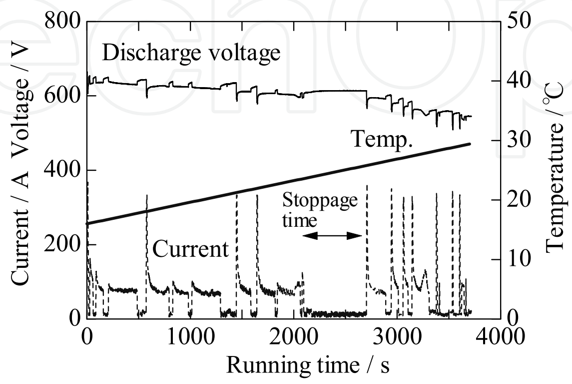

Fig. 7. Relations between running time and voltage, current, and temperature

4. Running test

4.1 Running test by DC type railcar

The running test of railcar with 45kWh lithium ion battery module was examined at Mikuni and Katsuyama business line of Echizen railway (Fukui city) in Japan. Mikuni business line was about 20km full length with a flat course and then railcar ran the one way only by lithium ion battery. Figure 7 shows the relations between running time and voltage, current and temperature on the flat course of the Mukuni line. The railcar ran for 20km when lithium ion battery module was discharged between 660V and 540V and this running included coasting and stopping several times. A current of 350A flowed to lithium ion battery module when the railcar was quickly accelerated. After accelerating, the current drastically decreased to about 80A, which was maintained continuously during running. After 3600s, the temperature of lithium ion battery module reached to 30°C. It was found that lithium ion battery module exhibited higher safety for the running.

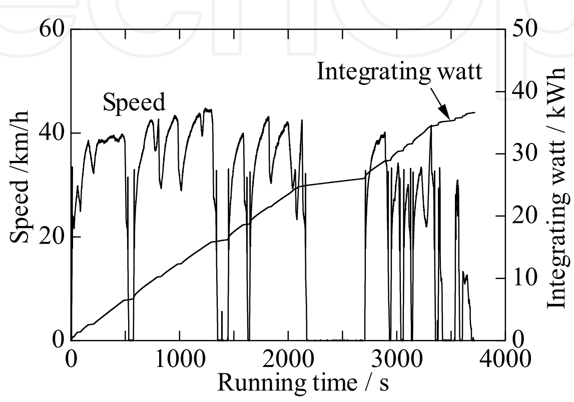

Fig. 8. Relation between running time and speed and integrating watt

Figure 8 shows the relation between running time and speed and integrating watt. On the running test, 37kWh electric power was consumed over 3600s of running and mileage was 0.54km/kWh.

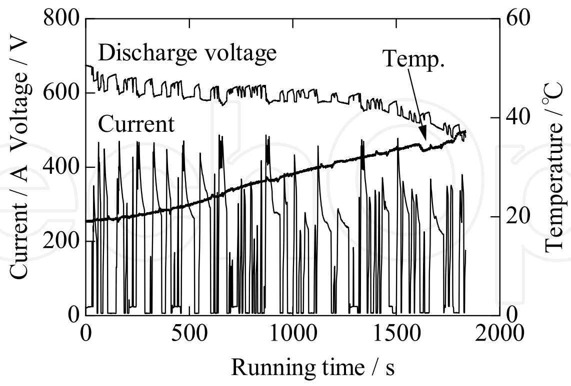

Fig. 9. Relations between running time and voltage, current, and temperature

By contrast, on an identical running test of a contact-wire railcar, 66kWh of electric power was consumed. The mileage was 0.3km/kWh. This poorer performance may result from not only loss of energy generated under power transmission from the substation but also power loss due to contact resistance between the contact-wire and pantograph. The use of the battery appeared to solve these problems. The running test of the railcar driven by a lithium ion battery indicated that its performance was comparable to that of contact-wire type railcar and that mileage was improved about two fold. Using the lithium ion battery, a running test under a condition of high load was also carried out on the Katsuyama line, which rises 150m on a sloping course with a 4% gradient. This running test used a 60kWh lithium ion battery module to which a 15kWh lithium ion battery module was added.

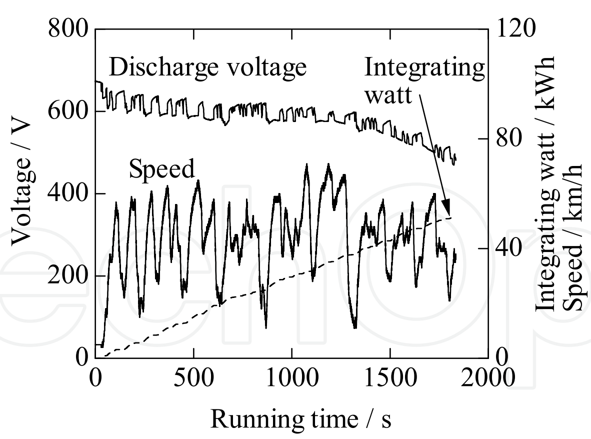

Fig. 10. Relation between running time and speed and integrating watt

Figure 9 shows the relations between running time and voltage, current and temperature on the Katsuyama business line. The railcar ran for 23km when lithium ion battery module was discharged between 660V and 490V. The current flowed at more than 400A when the railcar was quickly accelerated. After running for 23km, the temperature increased to around 40°C. Lithium ion battery module also exhibited higher safety for running with higher load.

Figure 10 shows the relations between running time and voltage, current, and temperature. On the test, 50kWh electric power was consumed over 1800s and mileage was 0.45km/kWh. 65km/h of maximum speed was recorded by the driving of lithium ion battery. For the contact-wire railcar, however, after running the same 23km course, 55kWh electric power was consumed and mileage was 0.41km/kWh. On this sloping course, the use of lithium ion battery module showed a 9% improvement in mileage. These results of running test suggest that lithium ion battery was expected as driving system of diesel car.

4.2 Running test by VVVF type railcar

Figure 11 shows the relation between running time and voltage, current and temperature after the running of VVVF type railcar with lithium ion battery. VVVF type railcar ran for 1.5km, while the power running, coasting and stopping were repeated in three times. A current of 300A flowed to lithium ion battery and the voltage was dropped when the railcar was quickly accelerated. When the current decreased down to about 200A, the rapid speed down was tried by using regenerative brake from 50km/hr to 40km/hr.

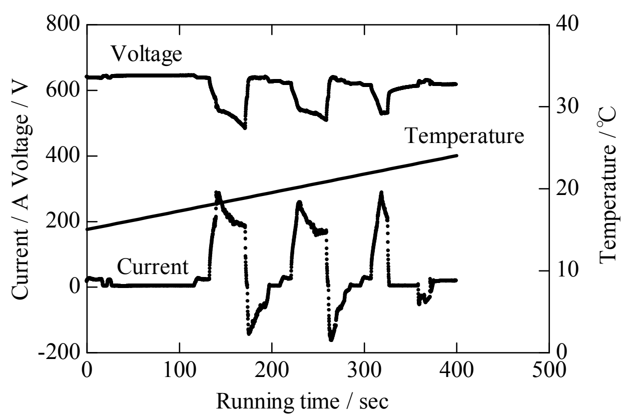

Fig. 11. Relations between running time and voltage, current, and temperature

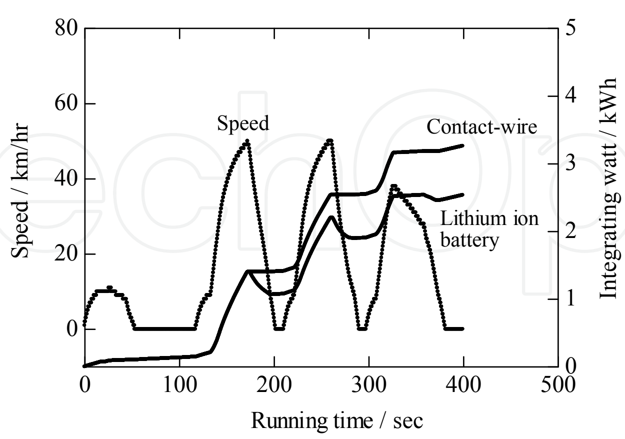

Fig. 12. Relation between running time and speed and integrating watt

The current of about -150A was obtained as regenerative energy. This suggested that 150A of regenerative energy was quickly charged to lithium ion battery by the regenerative brake. This means that lithium ion battery is charged at rate of 4.68C because 1C is equivalent to

32A. The temperature of lithium ion battery module increased from 17 to 25°C. It was found that the safety of lithium ion battery module could be maintained if the railcar was only used for the running of few km.

Figure 12 shows the change of speed and integrating watt after the running of VVVF type railcar by lithium ion battery and contact-wire. The maximum speed of 60km/hr was achieved in this work when VVVF type railcar was only derived by lithium ion battery. The integrating watt of lithium ion battery was 2.54kWh when VVVF type railcar ran for 1.5km while it repeatedly decelerated from 50km/hr by the regenerative brake. On the other hand, the electric power of 3.24kWh was consumed without lithium ion battery for the running of 1.5km. It was found that the energy-saving effect was about 22%.

4.3 Charging test from contact-wire

The quick battery charger apparatus (84Ah) which was received electric power from 600V contact-wire was developed. For charging test at constant current, lithium ion battery module which 80kWh of electric power was consumed after the running was used. The voltage of charge ranged from 550V to 660V. 80kWh of lithium ion battery module was charged up to SOC of 100% at 1C. Figure 13 the relation between charging time and voltage, current, temperature and integrating watt. After charging, the temperature of lithium ion battery module increased from 25°C to 33°C. It was found that 84Ah of lithium ion battery module could be charged at 600V safely.

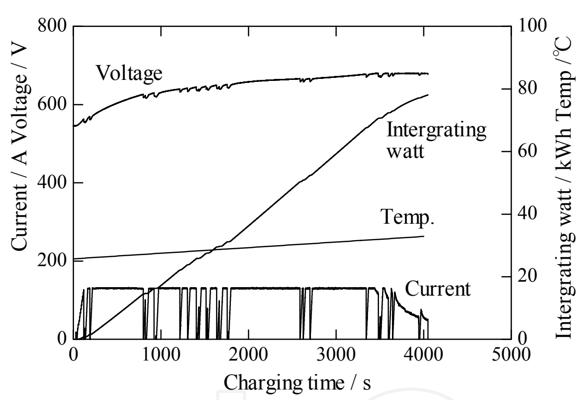

Fig. 13. Relation between charging time and voltage, current, temperature and intergrating watt

4.4 Rechargeable performance of lithium ion battery module

The rechargeable characteristics of lithium ion battery submodules were also examined after the running test for three years. The submodules were regularly charged for three years and 34V of voltage was maintained at room temperature. Figure 14 shows the relation between voltage and discharge capacity of lithium ion battery submodule at a rate of 1C. The initial discharge capacity of it was 34.2Ah, but decreased to 23.9Ah after three years. It was found that the discharge capacity of lithium ion battery submodule decreased to about 70% of initial discharge capacity. Lithium ion battery submodule had relatively high retention. The cycle performance of used submodule was examined at a rate of 1C under the charge condition on SOC of 80% and SOC of 100%.

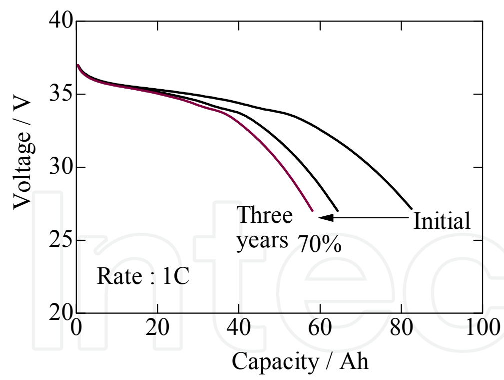

Fig. 14. Relation between voltage and capacity of submodule

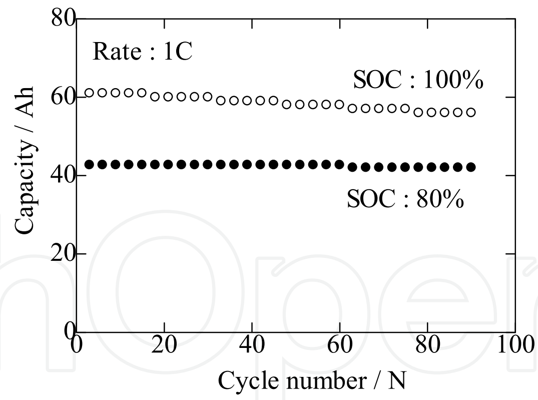

Fig. 15. Relation between capacity and cycle number of submodule at a rate of 1C

Figure 15 shows the relation between capacity and cycle number of used submodule. The capacity of submodule gradually decreased when the charge was carried out at SOC of 100%. On the other hand, the submodule exhibited high cycle stability at SOC of 80%. This result suggests that the full rechargeable is unfavourable to maintain high stability for large lithium ion battery module. The electric capacity may be lost to some extent, but the rechargeable of about 80% is desirable for the longer life cycle.

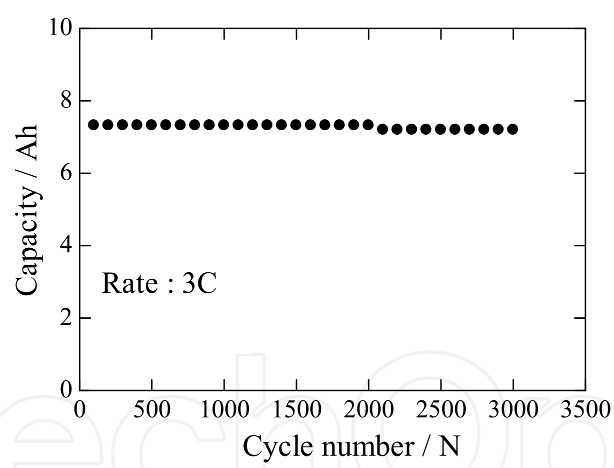

Fig. 16. Relation between capacity and cycle number of submodule at a rate of 3C (DOD 20%)

Figure 16 shows the cycle performance of used submodule was also examined by assuming the running of LRT with lithium ion battery in the road area. The distance of road area was 2km. 3000 times of cycle test was examined at room temperature. This means that 20% of DOD (depth of discharge) was continuously charged for 20min (3C) at every day for 24 month if lithium ion battery is charged at 4 times for one day from the service diagram of local railway. It was clear that the module had high stability for rechargeable. In the present circumstances, it was considered that the use of lithium ion battery was effective for the service diagram of local railway without high frequency.

5. Conclusion

Large lithium ion battery was developed for the running of railcar. Mn type lithium ion battery was used because of low cost and higher safety. LMP with high rechargeable performance were produced by large flame type spray pyrolysis. The laminate sheet type lithium ion cell was made using LMP. Various type large lithium ion battery modules consisted of submodule, in which laminate sheet type lithium ion cells were connected in series and parallel, were constructed.

The running test of DC and VVVF type railcar was carried out by using Mn type lithium ion battery at two business line of local railway in Japan. The results were obtained as follows;

(1) The running performance of railcar with lithium ion battery was equivalent to that of railcar which the electric power was supplied from contact-wire.

(2) Lithium ion battery had also the high running performance under a condition of high load.

(3) The high safety of lithium ion battery was maintained for the running of railcar.

(4) 22% of mileage was improved when the regenerative energy was charged by lithium ion battery during the running of VVVF inverter type railcar.

(5) The combination of lithium ion battery and VVVF inverter was effective for energy-saving of the railcar.

(6) The charge was performed at 600V safely by quick battery charger apparatus.

(7) The initial capacity of lithium ion battery decreased to 30% after the running test for three years.

(8) The used submodule exhibited excellent cycle stability.

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