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Relationship between the total energy efficiency of a sodium–sulfur battery system and the heat dissipation of the battery case

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Abstract

The relationship between the total energy efficiency of an Na/S battery system and the heat dissipation through its battery case, was investigated. The total energy efficiency was heavily influenced by the heat dissipation of the battery case, and little influenced by the energy efficiency of its cells. In order to obtain a higher total energy efficiency, it is essential to design the battery case with less heat dissipation. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Na/S battery; Energy efficiency; Heat dissipation

1. Introduction

The sodium–sulfur (Na/S) battery has several advantages [1,2] such as high energy density, low material cost and easy maintenance owing to a completely sealed type structure. Due to these advantages, the Na/S battery is expected to be utilized in load-leveling applications [1,3].

Since the operating temperature of the Na/S battery is about 290–380°C, it is enclosed in a thermally insulating battery case, to reduce the energy loss caused by heat dissipation [4].

To utilize an Na/S battery system in a load-leveling application, it is necessary not only to reduce the system cost to a level equivalent to or less than that of pumped hydro-storage power station, but also to achieve the total energy efficiency the same as that of pumped hydro-storage power-station (total energy efficiency: 70%).

This paper reports the relationship between the total energy efficiency and the heat dissipation of a 100-kW Na/S battery system, and discusses the way to increase the total energy efficiency.

2. Experimental

2.1. Cell construction

The construction of a single cell is shown in Fig. 1. Molten sodium metal, which serves as the negative electrode, is contained in a β″-alumina tube with a porous metal wick. The β″-alumina tube is sealed with glass

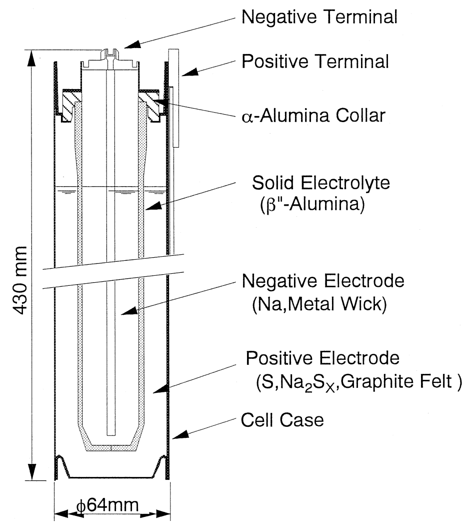

Fig. 1. Cross-sectional view of ceramic battery cell.

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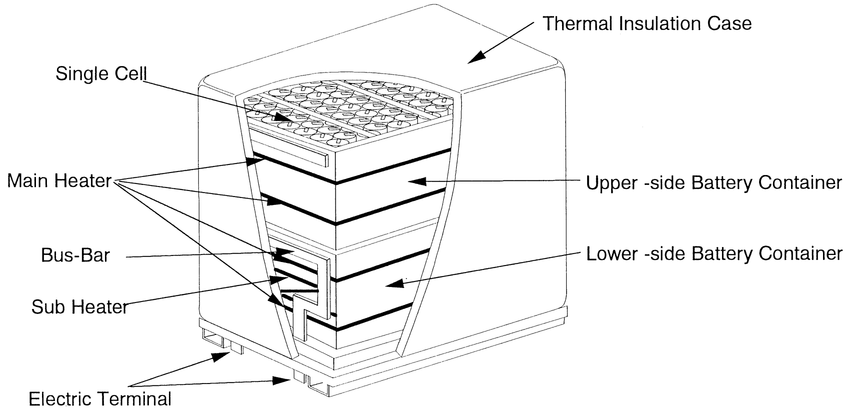

Fig. 2. Cut-away view of the 25 kW sub-module.

solder to an α-alumina header which electrically insulates the positive electrode from the negative electrode. The α-alumina header is sealed to the positive cell container made of chromized stainless steel and to the negative cell cover with aluminum washers by thermal compression sealing. A pre-cast matrix of graphite felt impregnated with molten sulfur, which serves as the positive electrode, is placed in a gap between the β″-alumina tube and the cell container.

2.2. Module construction

A 25-kW sub-module consisted of 10 series-connected cell blocks, each having eight 4-series-connected cells connected in parallel. Therefore, the 25 kW sub-module was composed of 320 cells. This inter-connected cell pack was enclosed in a vacuum type thermal insulation case.

Fig. 2 shows the construction of the 25 kW sub-module. Fig. 3 shows the heater positions and temperature measuring points of the 25 kW sub-module. The 25 kW sub-module was equipped with two main-heaters (1.0 kW each) and one sub-heater (0.5 kW), to keep the inner battery temperature between 290–380°C. The two main-heaters were controlled individually by the temperature measuring points 2 and 3, and the sub-heater was controlled by the temperature measuring point 5. All the heaters were controlled by the same setting temperature.

A 100-kW module was composed of four 25-kW sub-modules connected in series. Table 1 summarizes the specifications of the single cell, 25 kW sub-module and 100 kW module.

2.3. Heat dissipation of battery case

Heat dissipation of the 25 kW sub-module case was determined by measuring the electric heater power consumption to keep a temperature set in the thermal insulation case for 1 week without charges or discharges.

2.4. Energy efficiency

The energy efficiency of the 100 kW module in a nominal charge/discharge pattern was measured with a variety of temperature settings. The 100 kW module was

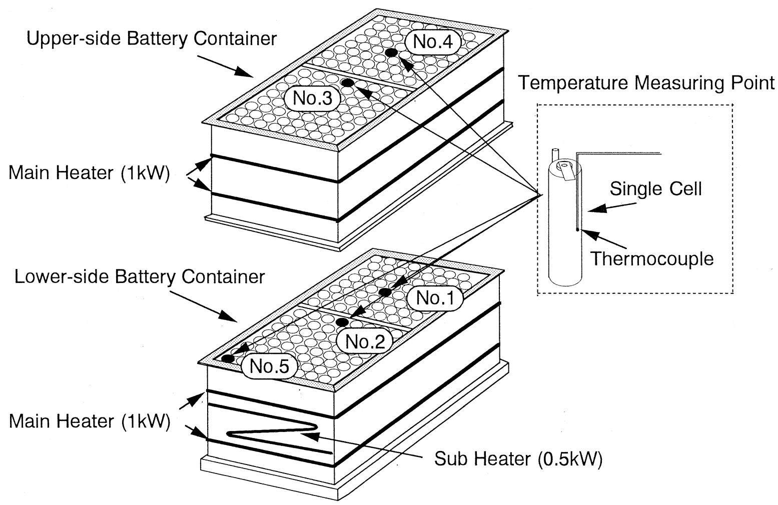

Fig. 3. Heater positions and temperature measuring points of the 25 kW sub-modules.

Table 1
Specifications of the 100 kW module, the 25 kW sub-module and the single cell

Item	100 kW Module	25 kW Sub-module	Single cell
Output power	100 kW	25 kW	80 W
Battery energy	400 kW h	100 kW h	320 W h
Output voltage (DC)	285 V	71 V	1.82 V
Output current (DC)	352 A	352 A	44 A
Nominal capacity	1408 A h	1408 A h	176 A h
Connection	Sub-module × 4S	(4S × 8P) × 10S	–
Number of cells	1280	320	–
Size	1576 W × 1386 L × 2288 H (mm)	710 W × 1371 L × 1117 H (mm)	ϕ 64 × 430 H (mm)
Weight	7500 kg	1700 kg	2.7 kg

discharged at a constant power of 100 kW for 4 h. After 8 h rest, it was charged at a constant power of 59 kW to return the ampere-hour (Ah) capacity discharged. The nominal daily pattern consisted of discharge: 4 h, rest: 8 h, charge: about 8 h, and rest: about 4 h.

The nominal weekly pattern consisted of a successive 5-day daily pattern followed by a 2-day rest. These nominal charge/discharge patterns were chosen based on the expected consumer's operation in load-leveling.

2.5. Definition of energy efficiency

In this paper, four different energy efficiencies were discussed.

First is the energy efficiency of the battery, η_1. Second is the energy efficiency of the battery including the electric heater power consumption, η_2. These two energy efficiencies were calculated as DC energy on a daily basis.

The third efficiency is the daily total energy efficiency including electric heater power consumption and the efficiency of the inverter which is assumed to be 95% in one direction, η_3. The fourth efficiency is the weekly total energy efficiency including electric heater power consumption in the 2-day rest, η_4. The last two energy efficiencies were calculated as AC energy.

From the standpoint of load leveling use, the weekly total energy efficiency is the most important energy efficiency to evaluate the sodium–sulfur battery performance.

Table 2
Definition of energy efficiencies

The energy efficiency of the battery, η_1	$\eta_1 = A/B$
The energy efficiency of the battery including electric heater power consumption, η_2	$\eta_2 = A/(B+C)$
The daily total energy efficiency, η_3	$\eta_3 = AX/(B+C)$
The weekly total energy efficiency, η_4	$\eta_4 = 5AX/(5B/X+7C)$

A: The discharge energy of Na/S battery module.
B: The charge energy of Na/S battery module.
C: The electrical heater power consumption for a day.
X: The efficiency of the inverter in one direction.

The definitions of these energy efficiencies is summarized in Table 2.

3. Result

3.1. Heat dissipation of battery case

Fig. 4 shows the relationship between the operating temperature and the heat dissipation of the battery case. The heat dissipation of the battery case increased remarkably with increasing operating temperature. This is attributable to an increase in the temperature difference between the inside and the outside of the battery case. This result suggested that decreasing the energy loss from the Na/S battery system required a lower operating temperature.

3.2. Energy efficiency

Fig. 5 shows the operating characteristics of the 100 kW module at 315°C on the nominal weekly test pattern.

The operation of the 100 kW module was stopped on weekends for 2 days at the fully charged state, and was resumed the following week.

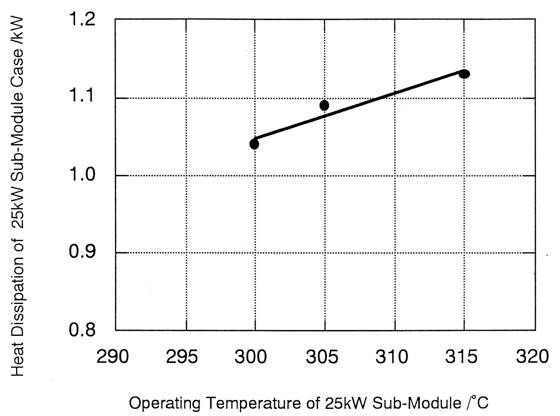

Fig. 4. Relationship between the operating temperature and the heat dissipation of the battery case.

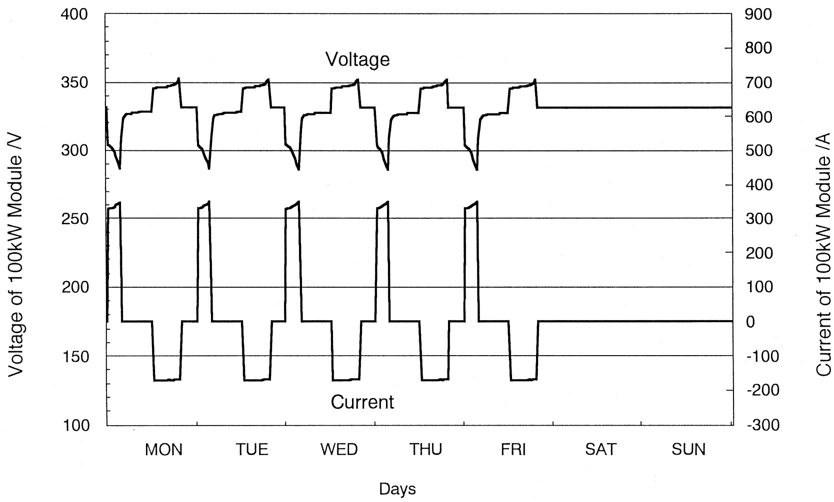

Fig. 5. Change in current and voltage of the 100 kW module in a nominal weekly test.

The weekly energy efficiency of the 100 kW module was measured with this nominal weekly test pattern.

Fig. 6 shows the maximum and minimum cell temperatures and electric heater power consumption of the 100 kW module in the nominal weekly test pattern.

The maximum cell temperature rose rapidly by about 40°C during discharging because of the exothermic electrochemical reaction coupled with Joule heat associated with the internal resistance, and fell gradually during the charging and the resting period.

The maximum cell temperature returned to the original temperature before the beginning of the next discharge.

The electric heater power was mainly consumed during the charging and the resting periods, and most was consumed to keep the operating temperature at the weekends.

Fig. 7 shows the relationship between the operating temperature and the energy efficiencies of the 100 kW module. The energy efficiency, η_1, increased with increased operating temperature. On the contrary, the energy efficiencies η_2, η_3 and η_4 increased with decreased operating temperature.

This result showed that the energy efficiency, η_1, was mostly influenced by the internal resistance of the 100 kW module, while the energy efficiencies η_2, η_3 and η_4 were mostly influenced by the electric heater power consumption of the 100 kW module.

4. Discussion

It became apparent that the weekly total energy efficiency, η_4, was mostly influenced by the heat dissipation of the battery case, and least influenced by the energy efficiency, η_1.

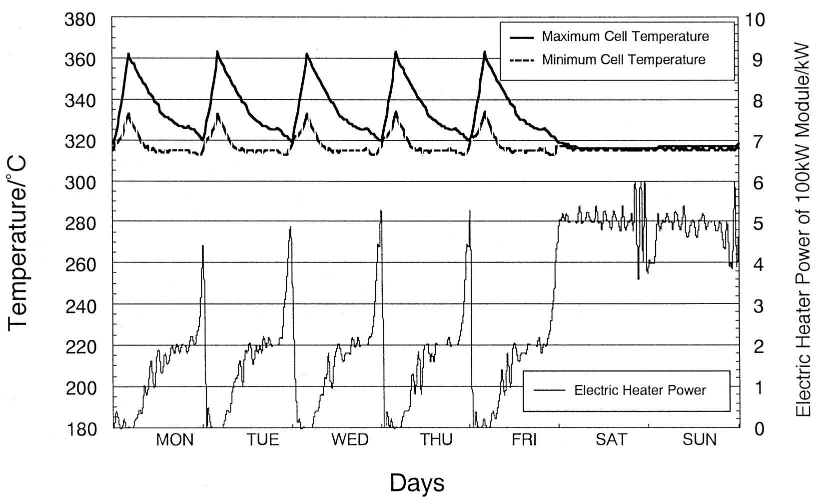

Fig. 6. Cell temperatures and electric heater power of a 100-kW module in a nominal weekly test.

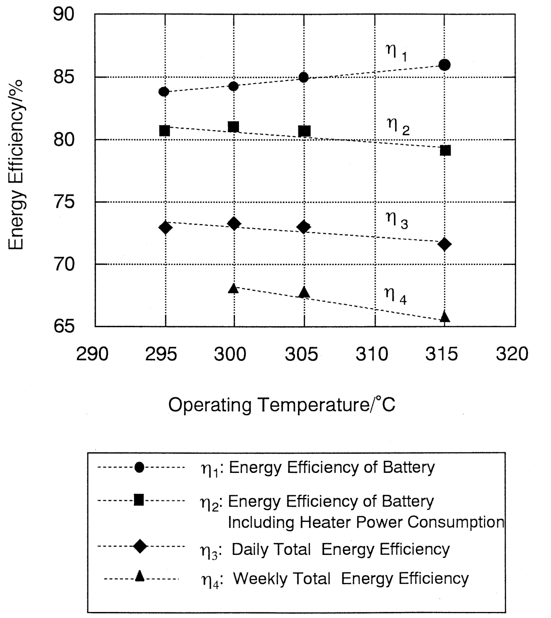

Fig. 7. Relationships between the operating temperature and the energy efficiencies of a 100-kW module.

The relationship between the energy efficiency and the heat dissipation of the battery case is discussed below.

Fig. 8 shows a schematic model of the heat balance in the 25 kW sub-module. There are two exothermic sources in the 25 kW sub-module, one is the electric heater and the other is the Na/S battery itself. Two exothermic reactions, which are the Joule heating associated with ohmic loss and the entropy-heat associated with the electrochemical reaction, occurring simultaneously in a Na/S cell.

Since the entropic heat is exothermic on discharging, and endothermic at charging, no heat generation or adsorption occurs in a full charge/discharge cycle. Therefore, only the Joule-heat influences the heat balance of the 25 kW sub-module.

For the temperature of the 25 kW sub-module not to overshoot the appropriate operating temperature range during discharging, the heat dissipation of the battery case is designed to be somewhat larger than the exothermic calorific value of the 25 kW sub-module [5].

So, the electric heater supplies the heat corresponding to the difference between the heat dissipation of the battery case and the exothermic calorific value of the sub-module.

In studying the relationship between the heat dissipation of the battery case and the energy efficiencies, we assume that an Na/S battery is operated 1 cycle/day and the average temperature of the sub-module at the beginning of discharge is constant for every cycle.

Electrical heater power consumption, C, can be expressed as a function of the hourly heat dissipation of the battery case, D, the discharge energy of the Na/S battery module, A, and the charge energy of the Na/S battery module, B

$$C = 24D - (B - A) \tag{1}$$

On the other hand, the energy efficiency of the battery, η_1, can be expressed as

$$\eta_1 = A/B \tag{2}$$

consumption, η_2, can expressed as

$$\eta_2 = A/(B + C) \tag{3}$$

Therefore, using Eq. (1), Eq. (3) can be rewritten as

$$\begin{aligned} \eta_2 &= A/(B + 24D - (B - A)) \\ &= A/(A + 24D) \end{aligned} \tag{4}$$

The daily total energy efficiency, η_3, can be expressed as

$$\eta_3 = AX/(B/X + C) \tag{5}$$

where X is the efficiency of the inverter in one direction.

Using Eqs. (1) and (2), Eq. (5) can be rewritten as

$$\begin{aligned} \eta_3 &= AX/(B/X + 24D - (B - A)) \\ &= AX/(A/\eta_1/X + 24D - A(1/\eta_1 - 1)) \end{aligned} \tag{6}$$

The weekly total energy efficiency, η_4, can be expressed as

$$\eta_4 = 54X/(5B/X + 7C) \tag{7}$$

and Eq. (7) can be rewritten as

$$\begin{aligned} \eta_4 &= 5AX/(5B/X + 168D - 5(B - A)) \\ &= 5AX/(5A/\eta_1/X + 168D - 5A(1/\eta_1 - 1)) \end{aligned} \tag{8}$$

Eq. (4) indicates that the energy efficiency of the battery including electrical heater power consumption, η_2, is independent of the energy efficiency of the battery, η_1, but dependent on the discharge energy of the Na/S battery module, A, and the heat dissipation of the battery case, D.

Eqs. (6) and (8) indicate that the daily and weekly total energy efficiencies, η_3, η_4 are determined by the discharge energy of the Na/S battery module, A, the heat dissipation of the battery case, D, and the energy efficiency of the battery, η_1.

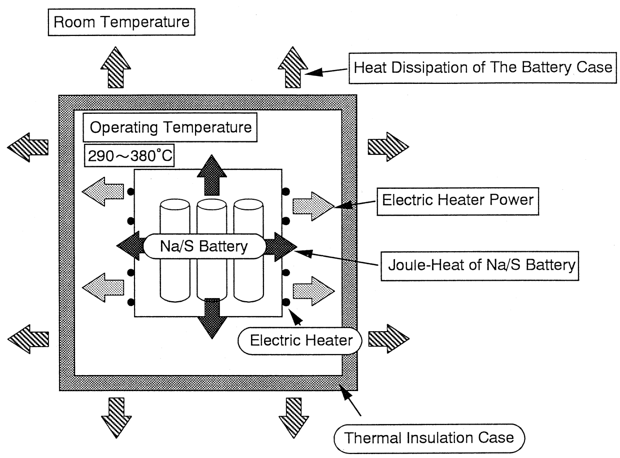

Fig. 8. Schematic model of the heat balance in a 25-kW sub-module.

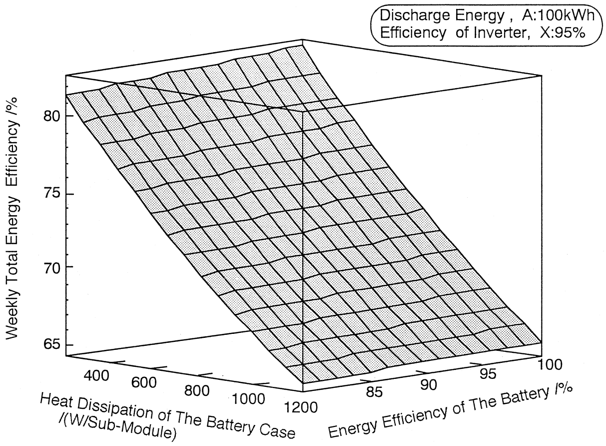

Fig. 9. Relationship between the weekly total energy efficiency, energy efficiency of the battery and heat dissipation of the battery case.

Fig. 9 shows the calculated weekly total energy efficiency, η_4, as a function of η_1 and D, using the above equations.

It is apparent that the weekly total energy efficiency, η_4, is largely influenced by the heat dissipation of the battery, D, and less influenced by the energy efficiency, η_1.

So, not only the energy efficiency of battery including electrical heater power consumption, η_2, but also the weekly total energy efficiency, η_4, are essentially influenced mostly by the heat dissipation of the battery case, D.

These findings are consistent with the experimental results shown in Fig. 7.

From a practical point of view, in order to raise the weekly total energy efficiency, η_4, it is essential to design a battery case with an appropriate heat dissipation, and to optimize the operating temperature rather than improve the energy efficiency of the battery, η_1.

This also means that even if the resistance of the Na/S cell increases during long term operation, resulting in the decrease in the energy efficiency of the battery, η_1, the weekly total energy efficiency remains almost unchanged.

However, the Joule-heat of the Na/S battery system increases with increased resistance, and finally the Na/S battery system cannot be operated, because the maximum temperature in the sub-module exceeds the operating temperature range.

The relationship between the weekly total energy efficiency and the heat dissipation of the battery case as discussed here, is not only an important matter for the Na/S battery system but also applies to other high temperature battery systems for load-leveling applications.

These results, therefore, are useful for other high temperature battery systems, such as the Li-polymer battery system [6,7].

5. Conclusions

The relationship between the total energy efficiency of the Na/S battery system and the heat dissipation of the battery case, was investigated.

Based on the present work, the following conclusions can be drawn:

(1) The weekly total energy efficiency is largely influenced by the heat dissipation of the battery case and less influenced by the energy efficiency of the battery.

(2) In order to raise the weekly total energy efficiency, it is important to design the battery case with appropriate heat dissipation, and to optimize the operating temperature rather than to raise the energy efficiency of the battery.

(3) These results are applicable to other high temperature battery systems, such as the Li-polymer battery system.

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