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Thermal Behavior and Insulation Strategies for Li-FeS_2 Thermal Batteries: An ANSYS Simulation Study

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Abstract

Thermal batteries are special electrochemical systems in which a great amount of energy is delivered during a relatively short period of time. The holding time of the thermal battery's working temperature and cell temperature define its discharge life. Thermal batteries have their advantages comparing other type of batteries, so they are used for several purposes including military field. Thermal batteries usually operate in the internal temperature range of 400 to 550℃. For that reason, it is important to analyze temperature field of thermal batteries to select and determine the insulation material and the thickness of that. This study discusses the thermal analysis of a thermal battery with ANSYS software. Thermal consideration should be done on all components of the thermal battery, and the design parameters of components of the thermal battery should be determined that can extend thermal lifetime to the maximum. To examine the correct solution value of thermal battery temperature field analysis by the ANSYS thermal analysis, analytic model is made since the structure of Li-FeS_2 thermal battery that was already developed and the temperature changing process inside thermal battery was considered by the analytic simulation method established in this study. To make the thermal battery operate in a regular way, a side heat insulation structure was designed. The result of simulation analysis of temperature changing process at the upper, lower and medium part of battery stack of the designed Li-FeS_2 thermal battery and result of discharge test proves that thermal design of Li-FeS_2 thermal battery satisfies technical properties required in the battery. In this research, a new method of calculating the thickness of insulation layer is reported and its correctness is ensured with ANSYS simulation.

Keywords: Thermal batteries, thermal design, thermal insulation

INTRODUCTION

Thermal batteries are special electrochemical systems in which a great amount of energy is delivered during a relatively short period of time. The discharge life of the thermal battery is determined by the holding time of its working temperature as well as that of the cell [1]. Thermal batteries have their advantages comparing other type of batteries, so they are used for several purposes including military field.

So, it is very important to build correct design method of thermal battery with computer simulation because of its special working conditions like high temperature. In this way, designing of insulation layer by simulation is necessary to secure not only the accuracy of design but also to reduce the research period [2].

In the past, the research on the thermal design of thermal battery had a big error. In many cases, they relied on the experimental method of installing the thermocouple inside the battery and measuring the temperature changing process inside the battery.

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In recent years, researchers have made the thermal model of thermal battery and analyzed temperature field by using CFD software Phoenics®, "Ether" code, LCCM Fortran Thermal Optimization Programs and so on [3–5]. But we made the analysis model because of real structure of the thermal battery and analyzed the temperature field of thermal battery by the ANSYS thermal analysis. In the present work, a transient model of heat generation and propagation within a Li/FeS_2 thermal battery is carried out using ANSYS program.

THERMAL DESIGN METHOD

Thermal consideration should be done on all components of thermal battery and the design parameters of components of the thermal battery should be determined that can extend thermal lifetime to the maximum.

The general thermal design process of thermal battery is as follows:

- Determining the necessary heat amount (amount of pyrotechnic pellet).
- Designing the double exothermal heat insulation layer and determining the design parameters.
- Determining the design parameters of lateral heat insulation layer.

Determination of Amount of Pyrotechnic Pellets

According to the abnormal heat conduction theory, freezing time to certain temperature is related to initial temperature [6]. The higher the initial temperature, the longer the working time. But initial temperature cannot be infinite because the rise in temperature accelerates the physical and chemical change of active materials in the thermal battery, thus decreasing the electric property of battery. Therefore, during the battery discharge the initial temperature is limited to some extent and it is called maximum allowable temperature.

On the other hand, the temperature inside the battery is increased by the heat generated during the burning process of pyrotechnic pellets. The amount of heat which is generated currently depends on pyrotechnic pellets. After all, when designing the thermal battery, the amount of pyrotechnic ("heat") pellets should be determined so that the internal temperature at the beginning of discharge can reach the maximum allowable temperature.

In Li-FeS_2 thermal battery, necessary number of pyrotechnic pellets is determined with the maximum allowable temperature of 600°C. Making the initial temperature reach the limited temperature of battery in the activated state is closely related to ensuring heat life of battery. The composition of pyrotechnic pellets used for analysis is 88% Fe powder and 12% $KClO_4$. It was impossible to put in the mass of pyrotechnic pellets as initial data in the analysis model, so it was converted as follows:

That is,

$$h = \frac{m}{\rho \cdot S}, \tag{1}$$

Where,

m: Mass of pyrotechnic pellets (kg),

ρ: Density of pyrotechnic pellets (kg/㎥),

S: Area of pyrotechnic pellets (㎡), and

h: Thickness of pyrotechnic pellets (m).

After all, in the analysis model, simulation test is done by converting the mass of pyrotechnic pellets into its thickness. Analysis result is given in Table 1.

Table 1. Simulation analysis result.

Mass of elementary pyrotechnic pellets (g)	7.0	7.2	7.4	7.6	7.8
Thickness of elementary pyrotechnic pellets (mm)	0.78	0.81	0.83	0.86	0.88
Initial maximum temperature (℃)	533.4	591.9	603.7	611.0	621.2

Calculating the amount of elementary pyrotechnic pellets to ensure the initial maximum temperature 600℃ according to Table 1 by the Lagrange interpolation formula, m=7.35 g. According to the result of battery manufacture and test, it is estimated that the most reasonable amount of elementary pyrotechnic pellets is 7.3~7.5 g. In the former design, unlike in new thermal design, the size of the plate and the number of pyrotechnic pellets to ensure necessary amount of heat are already determined.

Design and Design Parameter Determination of Double Heat Insulation Layer

The temperature change in the individual elementary batteries after the activation of thermal battery should be uniform. If the temperature at one of elementary batteries decreases earlier than others, discharge of this elementary battery ends, so the total voltage of the thermal battery decreases, and the battery shows rapid voltage drop [7]. The double heat insulation layer should be installed in the upper and lower part of the thermal battery to make the freezing speed uniform during the discharge of thermal battery, and of course, this double heat insulation layer should satisfy the above condition and structure parameters should be determined.

Design Parameter Determination of Side Heat Insulation Layer

To increase operating time of battery (that is, battery capacity), electrolyte should be maintained in liquid state and for this purpose, whole freezing speed must be reduced by designing effective heat insulation around the elementary batteries [8, 9]. Generated heat inside the battery escapes to the outside so the inner part rapidly freezes and the side heat insulation layer controls this freezing process thus extending the discharge time. In the thermal design of the battery, it is important to choose material for the side heat insulation layer that can extend discharge time as long as possible and determine the structural parameters. Especially, in the design of thermal battery with long life where operation for a long time must be ensured, it is very important to take reasonable measures to control the temperature decrease in the side of battery. The design process of side heat insulation structure is shown in Figure 2.

TEMPERATURE FIELD ANALYZING METHOD

It is very difficult to find the theoretical analytic solution by applying the above differential equation of abnormal heat conduction to the thermal battery. The ANSYS program is a powerful means to concretely reflect heat load conditions of thermal battery and perform the correct analysis. So, the temperature field of the thermal battery discharge process was analyzed using thermal analysis function of ANSYS.

The analysis was done as follows [10]:

Definition of Analysis Environment

In this step, ANSYS analysis environment is defined.

Definition of Material Property

To find the solution of simulation, thermal and physical characteristic values must be given such as specific heat of component, heat conductivity and density etc. as the reference data. But the components of thermal battery are composed of mixture of different components, so it must be calculated as thermal and physical characteristic values of mixtures, which are converted by Eqs. (1) and (2).

Making the Thermal Battery Analysis Model

Before making the thermal battery analysis model, assumption is made as follows:

- All the elements of thermal battery are assembled exactly without gap.

- There is heat transfer by heat conduction inside the thermal battery, and heat transfer by natural convection and heat radiation on the outer surface.
- During discharge, there is no heat quantity generated inside battery except that by the pyrotechnic pellets.

Based on the above assumptions, we reflect geometric sizes of the components inside the thermal battery as they are and make a thermal battery analysis model.

Elementary Division of Analysis Model

The above analysis model is divided into finite elements about the components of thermal battery.

Application of Load

The thermal loads affecting thermal battery include the natural convection and radiation on the outer surface of the battery and heat quantity in the pyrotechnic pellets. The initial temperature of thermal battery is determined as the temperature before discharge of thermal battery.

Initial condition is defined on every nodal point of divided elements.

Setting the Final Time and Time Step

Final time is set as discharge time of thermal battery and time step is set so that the combustion process of pyrotechnic pellets is reflected as it is.

Thermal Analysis and Result

After solving the problems defined above, the temperature changing process is considered on nodal points to be considered by the curve or table.

RESULTS AND DISCUSSION

Thermal simulation

To examine the correct solution value of thermal battery temperature field analysis by the ANSYS thermal analysis, analytic model is made based on the structure of Li-FeS_2 thermal battery that was already developed and the temperature changing process inside thermal battery was considered by the analytic simulation method established above (Figure 1).

The calculation result of thermophysical characteristic values of Li-FeS_2 thermal battery components by Eqs. (1) and (2) is given in Table 2 [11–13].

The calculation result of thermal load conditions is shown in Table 3.

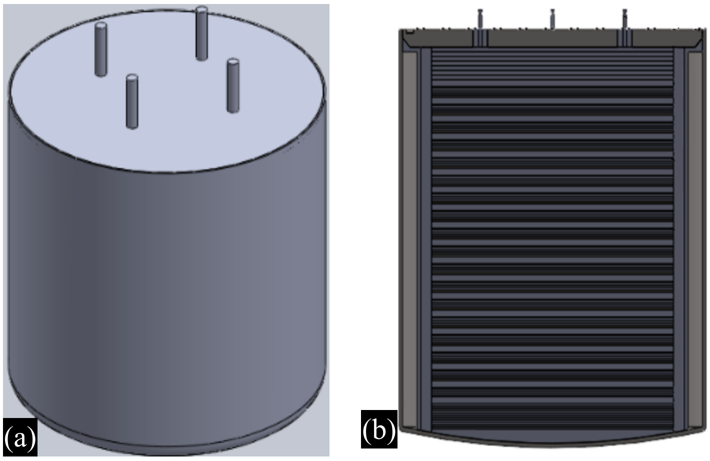

Figure 1. Analytic model of thermal battery: (a) Appearance, (b) Sectional view.

Time step and final time are set as follows:

- Time step: 0.02 s, and
- Final time: 400 s.

Under the above condition, we analyzed the temperature field of the thermal battery and then compared the temperature change at the central point of the battery side with measured values. Compared result between simulating result and measured values is shown in Table 4. Maximum error is 3.5℃ as shown in Table 4. After all, the error of this analysis method is less than 5%.

If the maximum temperature inside the battery is assumed to be 600℃, it is estimated that temperature field inside the battery is analyzed with error less than 30℃.

Design of Side Heat Insulation Structure

A certain temperature must be maintained to make the thermal battery operate in a regular way. And certain temperature must be maintained for a long time by putting the heat insulation material around the battery. The best heat insulation material is Min-K.

The composition of Min-K material is gaseous SiO_2 of 75%, quartz fiber of 9% and TiO_2 of 16%. Temperature change according to thickness of Min-K heat insulation layer is shown in Table 5. Temperature shown in the table is that at the central point of battery at 400 s, the end time of discharge.

Table 2. Thermophysical characteristic values of components.

No.	**Name**	**Specific heat (J/kg)**	**Density, (kg/m³)**	**Heat conductivity, (w/m℃)**
1	Anode (FeS_2 76%, LiCl 14.4%, Li_2S 1.6%, Mo 8%)	915	1912	4.24
2	Electrolyte (LiCl 18%, KCl 22%, MgO 60%)	913	2288	5.12
3	Cathode (LiSi alloy, Li 44%)	1112	1075	146
4	Pyrotechnic pellets (Fe 78%, $KClO_4$ 12%, Mo 10%)	760	1292	58.28
5	Heat conduction plate (Fe)	597	7500	46
6	Cover (stainless steel, 12Cr18Ni9Ti)	456	7801	17.9
7	External can (stainless steel, 12Cr18Ni9Ti)	456	7801	17.9
8	Upper, lower heat insulation slab (asbestos)	836	930	0.17
9	side heat insulation slab (Min-K, SiO_2 75%, quartz fiber 9%, TiO_2 16%)	670	330	0.02

Table 3. Calculation result of thermal load condition.

Thermal load condition	**Heat transfer coefficient (w/m³℃)**	**Ambient air temperature (℃)**	**Calorigenic rate (w/m³)**	**Calorigenic time (s)**
Result	5.67	20	$1.2 \cdot 10^{10}$	0.2

Table 4. Compared result with measured values.

Time (s)	5	10	15	20	25	30	35	40
Predicted value (℃)	36.6	55.2	71.7	86.7	102.5	112.6	123	133.9
Measured value (℃)	36	55	74	89	106	115	125	135
Error (℃)	0.6	0.2	2.3	2.3	3.5	2.4	2.0	1.1

Table 5. Temperature changes according to thickness of Min-K heat insulation layer.

Thickness (mm)	0	1.0	2.0	3.0	4.0	5.0	6.0	7.0
Temperature (℃)	410	440.8	459.3	465.2	466.6	466.8	466.1	465.0

The relation between temperature at the end of discharge and thickness of side heat insulation layer can be modeled as follows:

$$T_p = \frac{x}{a_0 \cdot x^2 + a_1 \cdot x + a_2} \tag{2}$$

Where,
x: Thickness of side heat insulation layer (mm), and
$a_{0\sim2}$: coefficient.

Calculating the corresponding coefficient according to Eq. (3) from Table 5, the following equation can be written.

$$T_p = \frac{x}{1.04 \cdot 10^{-5} \cdot x^2 + 2.0474.10^{-3} \cdot x + 0.2141 \cdot 10^{-3}} \tag{3}$$

Where,
x: Thickness of Min-K heat insulation layer (mm).

Compared result of calculated values with simulation values is shown in Table 6.

Table 6 shows that Eq. (3) exactly reflects the temperature change at the end of discharge according to the thickness of Min-K heat insulation layer. Calculating the thickness of heat insulation layer, x=4.5 mm. The maximum temperature at the end of discharge is 466.91℃, when x=4.5 mm.

Examination of Correctness of Thermal Design

The result of simulation analysis of temperature changing process at the upper, lower and medium part of battery stack of designed Li-FeS₂ thermal battery is shown in Figures 2–4.

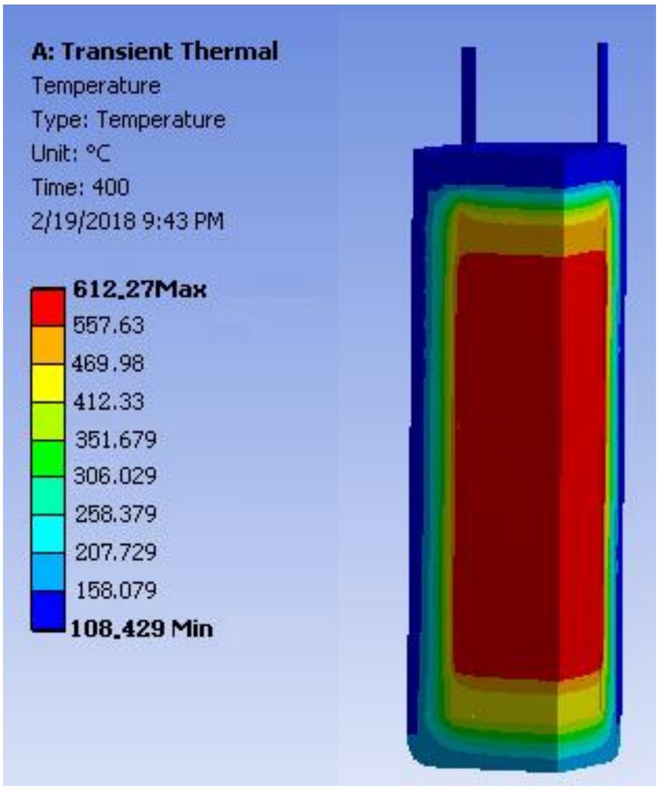

Figure 2. Thermal analysis process of thermal battery.

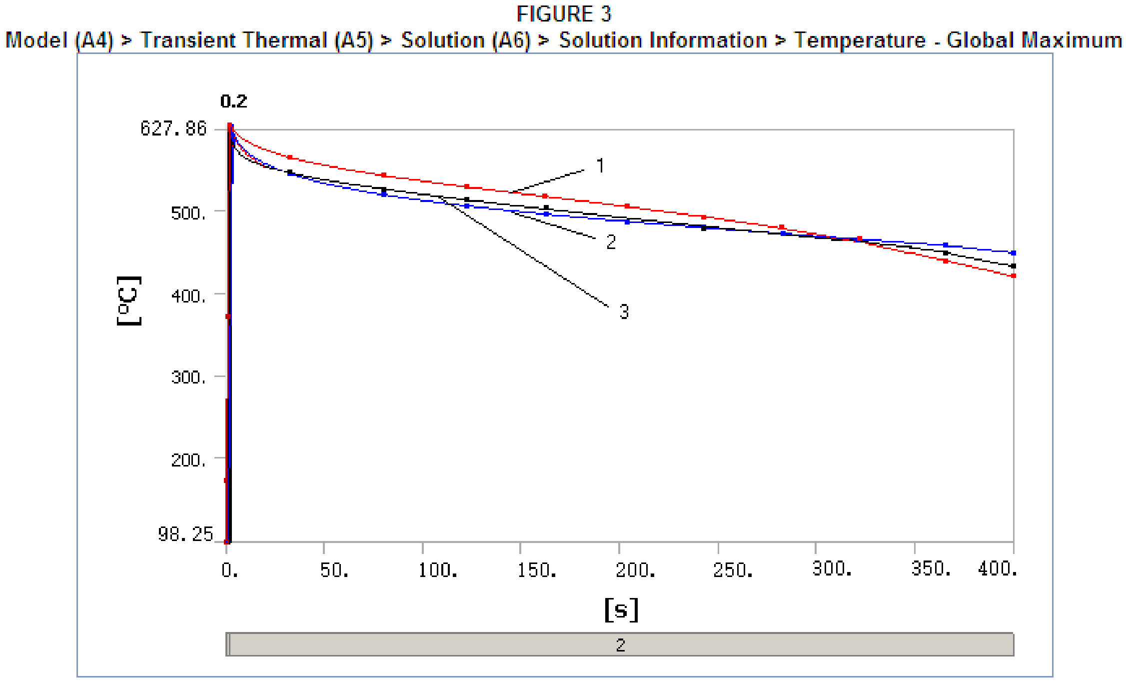

Figure 3. Temperature variation diagram of thermal battery during discharge process.
1: upper, 2: medium, 3: lower.

Table 6. Compared result of calculated values with simulation ones.

Thickness of side heat insulation layer (mm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Simulation result (°C)	440.8	459.3	465.2	466.6	466.8	466.1	465.0
Calculated result (°C)	440.1	459.7	465.1	466.7	466.8	466.1	464.9
Error (°C)	0.7	0.4	0.1	0.1	0	0	0.1

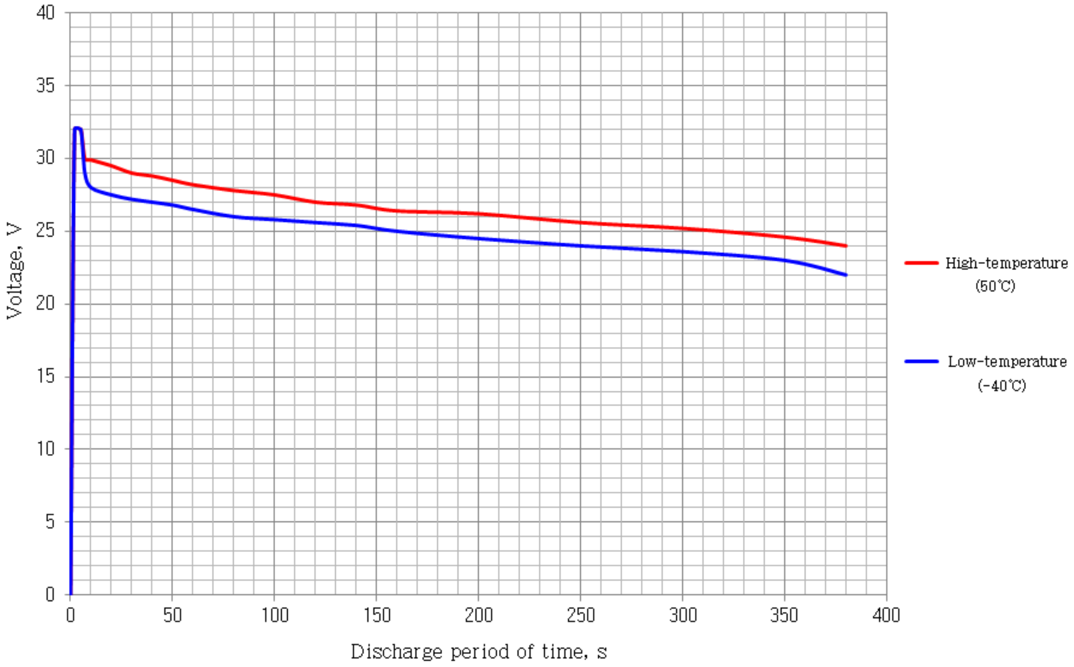

Figure 4. Result of discharge test.

1. *High-temperature discharge test (50℃),*
2. *Low-temperature discharge test (–40℃)*

As shown in Figure 4, temperatures at the end of discharge process at upper, medium and lower part of designed Li-FeS_2 thermal battery stack, are 451.12, 455.58, and 452. 42°C respectively, so they are all satisfactory in usable temperature range of battery and the temperature difference is less than 5°C.

So, the designed Li-FeS_2 thermal battery satisfactorily ensures thermal life. The correctness of thermal design of Li-FeS_2 battery is examined through discharge test. During the discharge test, constant-current discharge was done at 5 A according to the technical requirements.

The result of discharge test is shown in Figure 4. As shown in Figure 4, the designed thermal battery satisfied technical properties (more than 360 s) required in the high- and low-temperature discharge tests. This proves that thermal design of Li-FeS_2 thermal battery satisfies technical properties required in the battery.

CONCLUSION

The thermal design was performed through simulation analysis by means of the ANSYS program. In this research, a new method of calculating the thickness of insulation layer is reported and its correctness is ensured with ANSYS simulation.

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