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Heat Transfer Investigations in Thermally Activated Battery – Experimental and Numerical Studies*

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Abstract. In this paper both experimental and numerical studies of heat transfer in thermally activated batteries deriving from chemical sources of electric currents are considered. These batteries are used to supply special devices in the army, i.e. missiles, rockets and they are characterized by the activation time from 0.1 s to several seconds with an effective working time from seconds, to tens of minutes [1]. The heat being generated during their work inside the battery causes a temperature increase of up to 873 K. In the frame of this work both experimental and numerical investigations of temperature distribution on the outer surface of the thermally activated battery BTR-03, as well as the heat flux distribution were carried out [8]. Comparing the temperature histories at several points on the outer surface of the battery BTR-03, obtained from experiment and calculated numerically allowed to validate the numerical model of heat transfer in the battery.

Keywords: materials engineering, measurement of temperature, thermally activated battery

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1. INTRODUCTION

The considered thermally activated batteries are characterized by high mechanical strength, reliability over a wide temperature range, freedom from maintenance during storage and long shelf life.

The values of voltage and currents are adjusted to the requirements of the user [1, 2]. In the case of battery BTR-03 it was assumed that battery life did not exceed 660 s [1, 2]. Structure of the thermal battery BTR-03 is based on the electrochemical system $Ca/LiCl,KCl/PbSO_4$ [1, 2, 8]. An anodic reaction mechanism is presented in the paper by Nissen [5]. The battery consists of multiple cells connected in series. The individual elements forming the basic component, a single cell, are made in the form of flat rings arranged in the following way: calcium anode, secondly an electrolyte layer which is a mixture of salts *LiCl* and *KCl* and the cathode which is made of $PbSO_4$. Individual cells are separated by the pyrotechnic heat tablets – Fig. 1 [1]. In a temperature range of (-)50°C to (+)50°C the electrolyte is solid, showing no ionic conductivity. The activation of the thermal battery occurs after the melting of the electrolyte salt, which is occurs as follows.

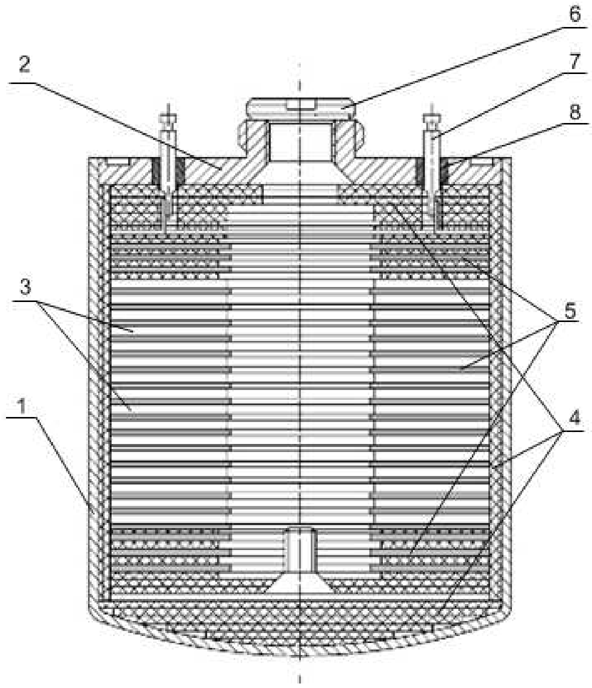


Fig. 1. Cross section view of thermal battery BTR-03: 1 – cup, 2 – lid, 3 – cell, 4 – battery thermal insulation elements, 5 – heat tablet, 6 – impact igniter, 7 – battery pole, 8 – pole insulation

Startup of the impact igniter mounted in the lid of the battery initiates an exothermic reaction of the pyrotechnic heat tablets. Generated heat energy that raises the temperature of individual elements of the battery to about 600 K, melts the electrolyte and initiates a redox reaction, which causes the emergence of voltage in each of the cells.

Completion of the battery life occurs in the case of the complete reaction of the respective electrode materials, or in the case of the solidification of the electrolyte. To prevent premature crystallization of the electrolyte, thermal insulation is placed inside the battery [1]. The battery BTR-03 is cylindrical in shape with a diameter of 56 mm, height of 74 mm and a weight not exceeding 450 g [1, 2].

2. BATTERY ACTIVATION

When the impact igniter of the battery BTR-03 initiates its activity, the flame fills the space inside the cylinder of the battery. The initiation of all 28 heat tablets occurs at exactly the same time. As a result of a consultation with the manufacturer of the BTR-03 it was assumed that the linear burning rate of the pyrotechnic heat tablet material was 5 cm/s and in 1 s all heat tablets were burnt [8]. All of the 22 heat tablets are connected with the 22 cells and located in the middle of the battery BTR-03. Three heat tablets are placed above a pile of 22 sets: a tablet-cell and 3 other tablets are placed under the pile. Additional tablets are separated from one another only by the thermal insulation layers of cardboard and they constitute the thermal protection of the cell pile from the top and the bottom. This prevents the premature crystallization of the electrolyte due to its cooling. A single tablet weighs about 1.8 g and has a volume of $1.154 \cdot 10^{-6}$ m^3. The manufacturer of battery BTR raises the calorific value of a single heat tablet in subsequent series. Initially its value was about 1600 J/g, followed by 1850 J/g. There is no current data on the calorific value of heat tablet of the battery BTR-03. In our case, the single heat tablet calorific value of 2600 J/g and BTR-03 battery activation time < 1 s was assumed [1, 2]. As a result a total heat flux of 130 kW is obtained from the battery during one second. Dividing this value by the volume of 28 heat tablets, we get the maximum value of a single tablet heat source equalling $4 \cdot 10^9$ W/m^3. Calculations of heat transfer in the battery BTR-03 were carried out within time intervals of 700 s which exceeds the burn time of tablets by 700 times. Therefore a constant value of volumetric heat source density in time of 1 s was assumed. Finally, in heat transfer model the volumetric heat source density as a function of $\dot{q}_v(t)$ – Fig. 2 with its maximal value equals $4 \cdot 10^9$ W/m^3 was assumed for doing calculation.

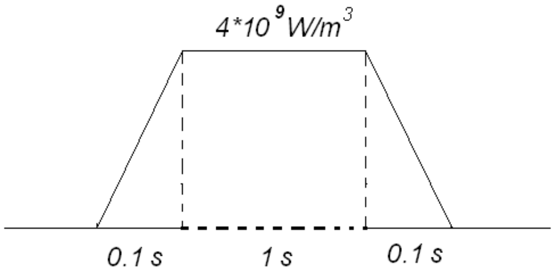


Fig. 2. Time-dependence of volumetric heat source density $\dot{q}_v(t)$ for the battery BTR-03 single heat tablet

3. EXPERIMENTAL ARRANGEMENTS

Temperature measurements in 6 points on outer surface of the battery BTR-03 were performed using coated thermocouples type *K* 0.5 mm in coat diameter by company Omega (USA). The location of thermocouples on the outer surface of the battery cup is shown in Figure 4. Thermocouples were glued with high temperature silicone glue (temp. max 873 K) *Red Hi-Temp RTV* (USA) and affixed to the outer surface of the battery cup using clips in the form of duralumin strips – Fig. 3. The battery was activated by a needle puncture of the impact igniter with a trigger. The trigger was activated with a direct voltage signal of 27 V. A set consisting of base unit NIcDAQ 9172 and a measuring card NI 9213 (National Instruments, USA) was used to measure temperature versus time *T(t)* at selected points on the outer surface of the battery BTR-03: a_0, a_1, a_2, a_3, a_4, a_5 (Fig. 4). Results of measurements are shown in Figs. 7÷12.

Fig. 3. View of the battery BTR-03 with mounted coated thermocouples which are used to measure the temperature on the outer surface of the battery cup

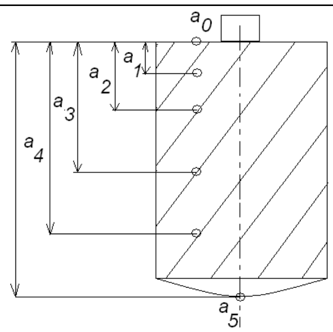


Fig. 4. Distribution of thermocouples along the length of the battery BTR-03: a_0 – 0 mm, a_1 – 10 mm, a_2 – 24 mm, a_3 – 45 mm, a_4 – 62 mm, a_5 – 74 mm

4. NUMERICAL EVALUATIONS AND EXPERIMENTAL RESULTS

Due to the high cost of the battery BTR-03 (about 1000 EU per unit) it is not possible to check the structural variants of the thermal insulation of the thermal battery, which is located in a special device. Thus, a preliminary numerical model of heat transfer in the battery BTR-03 suspended in the air that describes the performed experiment was created. Numerical calculations were carried out by means of COSMOS/M commercial software package. Four-sided mesh of 2320 elements and 2742 nodes was applied – Fig. 6. The results of finite volume method calculations were given in the form of the distribution of isotherms cross-section of the battery in successive time intervals – Figs. 13÷17. Also the results of calculations of the temperature dependence and heat flux density as a function of time in the chosen nodes of the mesh elements compatible with the measuring points $a_0 \div a_5$, i.e. $T_i(t)$ *and* $\dot{q}_i(t)$ were shown in Figs. 7÷12 and 18÷19. The initial boundary value problem, i.e. non-stationary heat transfer equation with internal heat sources (heat tablets) and boundary conditions of the third kind was solved. It was assumed that the battery life did not exceed 700 s. The problem was treated as two-dimensional due to the axial symmetry of the battery BTR-03. The results of calculations of the temperature dependence as a function of time $T(t)$ at the points: a_0, a_1, a_2, a_3, a_4, a_5 (Fig. 4) were compared with the experimental data and illustrated in Figs. 7÷12. Constant thermophysical properties of materials used to build the battery BTR-03 were assumed for numerical calculations – Table 1 and Fig. 5. The battery cup was made of the alloy steel 1H18N9T with a thickness of 1 mm – Fig. 5. Thermal insulation of cylindrical cup consists of three layers: the outer layer – insulation paper prespan with a thickness of 0.3 mm, the middle layer – micanite with a thickness of 0.15 mm, the inner layer – cardboard with a thickness of 1.5 mm. 22 sets: heat tablet and cell are located inside the battery cup. Three additional heat tablets are located above the pile of 22 sets and an additional three are located below the pile of 22 sets. Additional heat tablets are separated only by the thermal insulation layers of cardboard and are a thermal protection of the cell pile from the top and from the bottom. This is necessary to prevent premature crystallization of the electrolyte due to its cooling. Each heat tablet has a ring shape with a thickness of 0.7 mm, an outer diameter of 50 mm and an inner diameter of 19.5 mm. Each cell also has a ring shape with a thickness of 1.3 mm, an outer diameter of 50 mm and an inner diameter of 20 mm. The space above and below the cell pile is filled with thermal insulation cardboard – Fig. 5.

Table 1. Average values of material thermal properties adopted for numerical calculations: c_p – specific heat, k – thermal conductivity, ρ – density

material	c_p, J/(kg·K)	k, W/(m·K)	ρ, kg/m^3
1H18N9T [7]	460	26	8900
micanite [7]	880	0.52	3000
cardboard [7]	1340	0.20	500
substitute cell material: calcium anode+electrolyte+cathode* [6]	800	k_r = 50 (along the radius of battery) k_z = 4 (along the axis of battery)	5000
heat tablet [6]	800	1	2000
battery interior gas* [6]	1110	6	0.40

(* [6] – based on the data of electrolytes)

The temperature and the heat flux density distribution, i.e. $T_i(t)$ and $\dot{q}_i(t)$ on the outer surface of the cup battery BTR-03 was obtained as the solution of the heat transfer equation for the case of a heat source placed in cylindrical coordinates for a given initial and boundary conditions in a form [3, 4, 7]:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho \cdot c_p}\left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right] + \frac{\dot{q}_v}{\rho \cdot c_p},$$

where: T – temperature at a given point on the outer surface of the battery cup, t – the time from the initial moment, r, z – cylindrical coordinates of the point, k, ρ, c_p – thermophysical properties of materials of the battery BTR-03, $\dot{q}_v$ – volumetric heat source.

An ambient temperature was assumed as an initial condition T_{ambient} = 293 K. On the outer surface of the battery cup BTR-03 the heat transfer by convection and the boundary condition in the form

$$\dot{q} = \alpha \cdot \left(T_{ambient} - T_{battery\ cup\ surface}\right)$$

were established.

The assumed value of the coefficient of heat transfer is α = 15 W/(m^2·K). This is an overall coefficient, which was created as the sum of two components $\alpha = \alpha_{\text{convection}} + \alpha_{\text{radiation}}$, i.e. the coefficient of heat transfer for air and the coefficient of heat transfer associated with the heat transfer by radiation $\alpha_{\text{radiation}}$ = 5÷6 W/(m^2·K). In free space inside the battery BTR-03 there are mainly emissions from heat tablets. It was assumed that the heat transfer inside the battery took place only through the conduction of heat.

We do not include convection and heat transfer by radiation. In the axis of battery cylinder the gas properties were assumed as for air at 700 K and in accordance with the information given above, the heat transfer mechanism was assumed through conduction only. In the numerical calculations the changes of heat flux density on the outer surface of the battery cup BTR-03 were shown as a function of time along the radius $\dot{q}_r(t)$ at points: a_1, a_2, a_3, a_4 (Fig. 18) and along the height $\dot{q}_z(t)$ at points a_0, a_5 (Fig. 19), i.e. on the surface of the upper and lower lids of the battery cup BTR-03.

5. CONCLUSIONS

The temperature distribution measurements on the outer surface of the battery cup BTR-03 at selected points along the length of the battery and the preliminary numerical calculations carried out on currently available limited material data, helped to validate the model of heat transfer in the battery. Due to the high cost of battery it is not possible to take temperature distribution measurements of the battery cup inside the special device. Hence the design of the thermal insulation of the battery BTR-03 can be done only by numerical simulation. The enormous power of all 28 pyrotechnic heat tablets determines the heat transfer in the battery BTR-03. Hence, constant thermophysical coefficients adopted at the present stage of the development of the numerical model of heat transfer in the battery BTR-03: thermal conductivity, thermal diffusivity and specific heat (Table 1) are not – in the authors opinion – too simplistic. The authors see an opportunity to develop a numerical model of heat transfer in the battery BTR-03. At first, results of the heat transfer in a singular set, composed of the electrolyte, anode, cathode and the pyrotechnic heat tablet have to be obtained. The model should take into account the melting point of the electrolyte. Research on thermophysical properties of the electrolyte as a function of temperature is also needed.

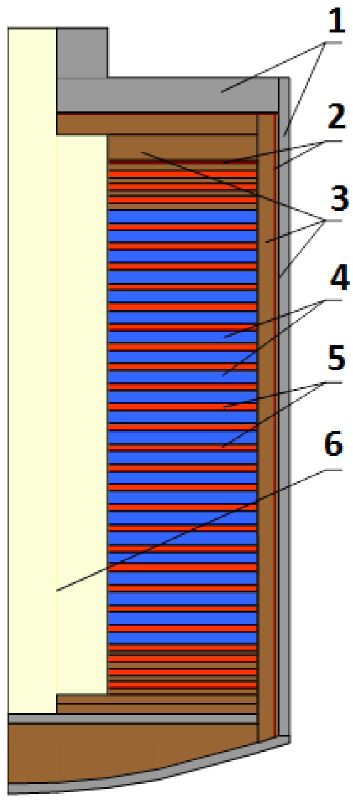


Fig. 5. Section of battery BTR-03: 1 – 1H18N9T, 2 – micanite, 3 – cardboard, 4 – substitute cell material, 5 – heat tablet material, 6 – battery interior gas

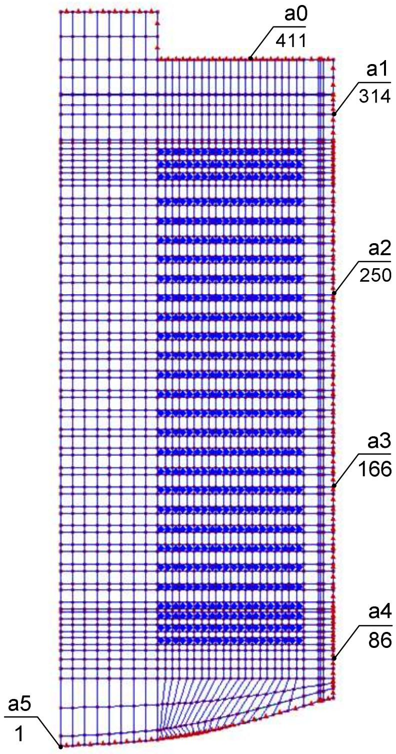


Fig. 6. Four-sided mesh of 2320 elements and 2742 nodes: Blue dots – volumetric heat source, Red dots – boundary conditions (replacement coefficient of heat transfer). Selected points: a_1, a_2, a_3, a_4 and the corresponding node numbers

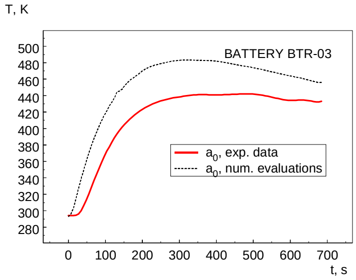


Fig. 7. Temp. distribution at point a_0

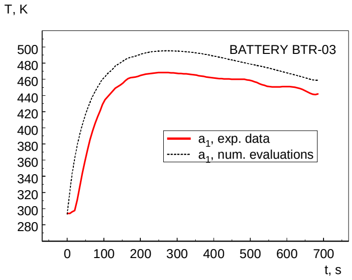


Fig. 8. Temp. distribution at point a_1

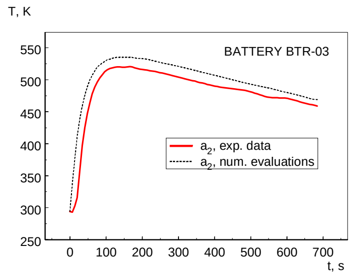


Fig. 9. Temp. distribution at point a_2

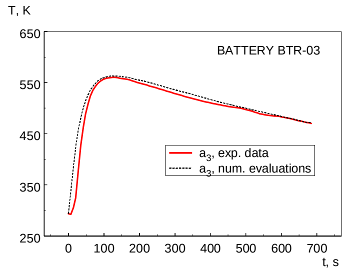


Fig. 10. Temp. distribution at point a_3

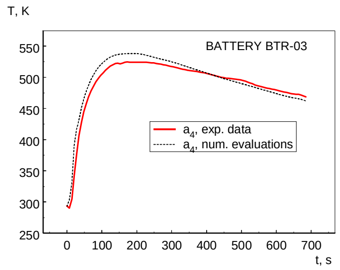


Fig. 11. Temp. distribution at point a_4

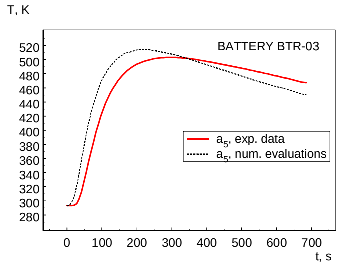


Fig. 12. Temp. distribution at point a_5

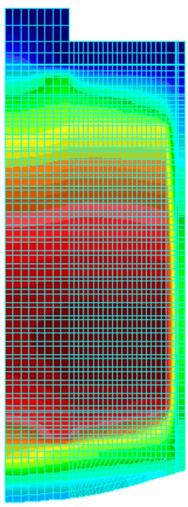


Fig. 13. Temp. distribution for t = 120 s

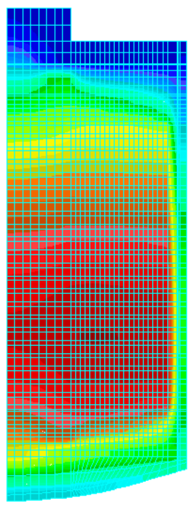
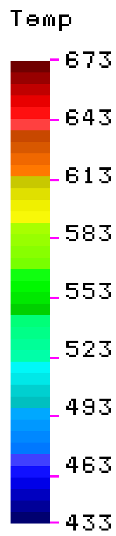


Fig. 14. Temp. distribution for t = 140 s



Temperature scale (Temp. in K)

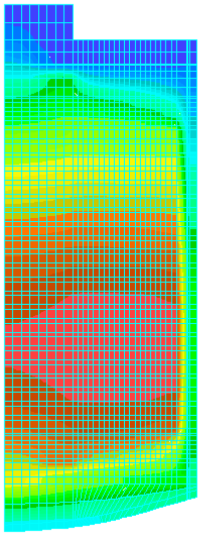


Fig. 15. Temp. distribution for t = 180 s

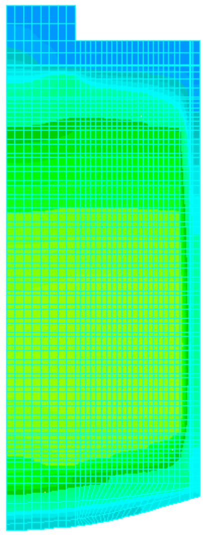


Fig. 16. Temp. distribution for t = 360 s

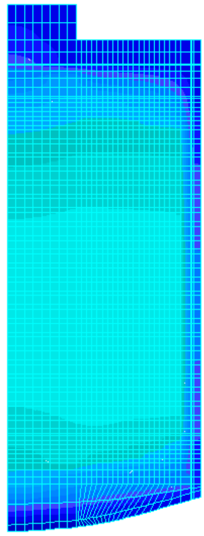


Fig. 17. Temp. distribution for t = 700 s

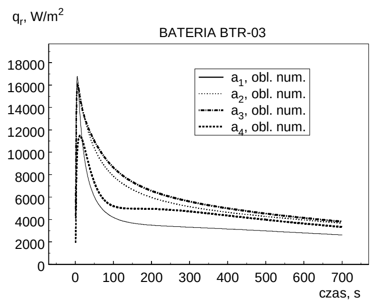


Fig. 18. Heat flux density history along the height $\dot{q}_z(t)$ on the cup surface at the points a_1, a_2, a_3, a_4

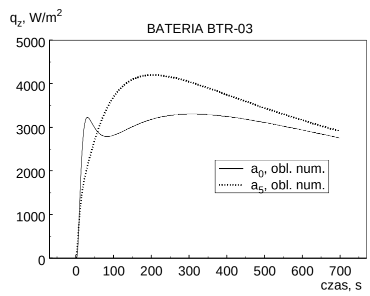


Fig. 19. Heat flux density history along the radius $\dot{q}_r(t)$ on the upper and lower lids at the points a_0 and a_5

The interior of the battery BTR-03 reaches a maximum temperature of 672 K after about 2 minutes from initiation. At that time, the outer surface of the cup reaches the maximum temperature of 583 K (Figs. 7÷12 and Fig. 13). The battery BTR-03 does not heat up symmetrically – Figs. 7÷12 and Figs. 13÷17. Therefore, the number of additional heat tablets above the pile of 22 cells should be increased from 3 units to 4 units. Heat dissipation through the lid of the battery cup is larger than through the bottom of the battery cup – Fig. 7 and Fig. 12.

According to the authors, in order to maintain the battery electrolyte in the liquid state for longer periods than currently, the numerical calculations with more additional heat tablets above and below the 22 cell pile should be carried out. Analysis of changes of heat flux density as a function of time $\dot{q}_r(t)$ on the outer surface of the battery BTR-03 cup at the points a_1, a_2, a_3, a_4 (Figs. 8÷11) confirms data from the manufacturer that the full power of the pyrotechnic heat tablets is already available in the first second. Analysis of changes of heat flux density as a function of time $\dot{q}_r(t)$ on the upper and lower lids of the battery BTR-03 cup $\dot{q}_z(t)$ leads to the conclusion that the heat flux density at these sites remains virtually constant from the initiation of the battery until the end. The numerical calculations of heat transfer in the battery BTR-03 presented in this paper allow the analysis of the battery as a heat source. The location of the battery in the special device has no significance, because the shape and the type of thermal insulation of the battery BTR-03 can be designed without expensive experimental studies.

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