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CONTENTS

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EXPERIMENTAL EVALUATION OF FIRE HAZARD OF LITHIUM-ION BATTERY DURING ITS MECHANICAL DAMAGE

Purpose. To experimentally determine the combustion temperature of a lithium-ion battery (LIB) due to mechanical damage to its case by a sharp object. At the same time, to determine the cooling-down time of the lithium-ion battery after combustion and the further mathematical description of this process.

Methodology. To achieve the set goal, a laboratory bench with the appropriate measuring equipment was prepared. For mathematical modelling of the cooling process, experimental values and methods for studying heat transfer processes in solid multilayer cylindrical structures were applied.

Findings. Experimental studies showed that the maximum temperature on the lithium-ion battery case reached 715 °C. In turn, the average values showed a temperature of 665 °C. The average cooling time to a temperature of 50 °C was at least 17 minutes. Mass loss studies showed that after combustion are complete, all elements lose about 53 % of their original mass.

Originality. The combustion temperature and cooling-down time of Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) LIB specifically have been determined for the first time. In parallel with experimental studies, mathematical modelling of the cooling process of the LIB was carried out using the theory of heat transfer. It was found that the results of the mathematical modelling correlate well with the experimental values. This approach allows, in the future, carrying out analytical studies on LIB without the need (where possible) to conduct experiments.

Practical value. Further implementation and application of the obtained mathematical model will make it possible to determine the cooling time, the possibility of heating other (adjacent) LIB to a critical temperature, the possibility of ignition from overload, various LIB using only geometric parameters without the need for experimental research. Determining the cooling time of the LIB after combustion is a valuable indicator since it allows one to practically estimate the time during the LIB remains a potential source of danger.

Keywords: *fire hazard, combustion temperature, lithium-ion battery, mechanical penetration*

Introduction. Every year, people's interest in alternative energy sources and ways to obtain and store them grows. Separately, it is worth mentioning the rapid growth of production and replenishment of vehicles with alternative energy sources, which today are actually beginning to gradually displace traditional vehicles with an internal combustion engine.

The most common and widely available source of permanent energy for today is lithium-ion batteries (LIB) which are able to meet the needs of people and are widely used in all-electric vehicles and dozens of electric devices.

Numerous studies have shown that LIB, especially large capacity, is an extremely flammable element which, if mishandled, can be a powerful source of ignition and contribute to the spread of fire in vehicles, electronic devices, or storage and maintenance areas.

The modern electric car can contain from 140 to 7,000 and more different in geometric shape and chemical composition of LIB [1], and violation of its stable operation can cause short circuits and, as a result, intense combustion with significant heat [2].

It is determined that the rate and nature of LIB combustion are influenced by a variety of factors, including ambient pressure [3], and the total heat release during their combustion increases with the number of elements themselves. A significant factor that will affect the nature of the combustion of LIB will be the chemical composition of the cathode or anode of LIB, which directly affects the rate and nature of combustion of each of the LIB [4].

Literature review. A large number of studies of various scientific institutions around the world are constantly focused on the study and identification of various factors, parameters of LIB before and during combustion. They investigate both individual elements and entire batteries, the factors that initiate the onset of combustion, the nature and intensity of the amount of thermal radiation, the dependence of the intensity of combustion on the composition of the battery, and so on.

Thus, in the study [4] a three-dimensional model was developed to study the effect of different battery materials, external heating conditions and heat transfer conditions on the behaviour of the thermochemical combustion reaction of LIB. The results show that batteries with $Li_4Ti_5O_{12}$ anode and $LiFePO_4$ cathode show better thermal safety and stability than other materials considered in the study. Increasing the melting temperature of the separator improves the temperature of the onset of the thermochemical combustion reaction and delays

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its occurrence. In addition, it was found that the heating position in the lower part of the LIB is more likely to cause combustion than other heating positions. Increasing the air velocity and lowering the ambient temperature help the LIB to remain stable for longer until a thermochemical combustion reaction occurs.

The aim of research [5] was to conduct experimental studies to determine the amount of thermal energy and temperature indicators of LIB format 18650 during combustion. The following LIB was chosen for research: $LiCoO_2$ – T-Energy ICR18650, Lithium-Nickel-manganese-cobalt oxide ($Li(NixMnyCo_{1-x-y})O_2$) – Panasonic CGR18650CG, and lithium iron phosphate ($LiFePO_4$) – K2 18650E, subject to a different state of charge (SOC). Its primary heating from a powerful source of 20–100 W preceded LIB combustion. As a result of research, the number of parameters was determined and recorded, and general approaches to the description of the thermokinetic model of the LIB combustion process were developed.

The efforts of scientists [6, 7] were aimed at assessing the danger of batteries with a total capacity of 50 Ah. $LiFePO_4$ battery consisting of five single cells at 10 Ah was selected as the object of study. It was found that the combustion of the battery begins when the temperature reaches the range of 175–180 °C. This critical temperature is related to the internal short circuit of the battery, which is the result of the melting of the separator. The maximum flame temperature can reach 1,500 °C. Similarly, in [7] a study was conducted to assess the risk of fire from electric vehicles during the combustion of a real LIB accumulator block.

The obtained scientific results are significantly supplemented by the works [8, 9] as they consider the rate of propagation of LIB 18650 format combustion depending on the place of primary ignition. Thus, in particular, in [9] it was found that within 240–280 seconds, combustion can spread to adjacent LIB, located in the unit.

In contrast to most of the studies presented above in research [10], experimental studies were conducted to determine the nature of combustion and combustion temperatures depending on the type and degree of mechanical damage to the LIB. A number of tests for LIB damage with both a blunt object and a sharp nail were performed. Several types were chosen as LIB, namely: cylindrical format 18650 – LG 2,200 mAh, model ICR18650 S3 ($LiFePO_4$), Panasonic 2,200 mAh, model CGR18650CG 9 ($LiCoO_2$), also prismatic LIB ($LiCoO_2$) with a capacity of 3,000 mAh took part in the study.

The results of the research showed that the temperature indicators and the nature of LIB combustion depend on the ambient temperature; the design of LIB has a significant impact as well. The average temperature during LIB combustion was 600 °C. Computed tomography confirmed that the presence of a strong core has a significant effect on the further course of the combustion reaction.

The actual continuation and addition of the previous study can rightly be considered in the following works whose purpose was to determine the critical indicators of LIB during combustion due to mechanical damage under different conditions. The results of the work determined that:

- with the decrease in ambient pressure, the TR trigger time becomes longer and the maximum surface temperature decreases [11];
- the gas released by TR becomes more toxic as the environmental pressure decreases [11];
- the average propagation time between adjacent LIBs is not much difference when the environmental pressure decreases, and when the 18650 battery module is distributed in a cylindrical shape, the thermal runaway propagation path is basically unchanged as the environmental pressure decreases [11];
- different penetration positions, thermal runaway reaction is more severe when the battery is penetrated at centre due to the faster propagation of thermal runaway [12];
- battery surface temperature is not positively correlated with penetration depth, and the temperature distribution becomes more nonuniform with the increasing penetration speed [12];
- LIB combustion is accompanied by the release of a significant amount of combustion products that directly affect the nature of combustion and depend on the chemical composition of LIB. The results of the study showed at least ten different types of toxic gases emitted during combustion caused by mechanical damage to LIB, among which are acrolein, HCl, COF_2; HF and formaldehyde, etc. [13];
- the electrochemical composition of LIB and its degree of charge have a direct impact on the nature of the LIB combustion caused by mechanical damage, namely nail penetration. In particular, temperature values can range from 122 to 812 °C [14].

In general, mechanical tests of LIB is a commonly used method for assessing their danger [15]. It is interesting to note that a number of countries around the world have their own standards for checking and testing LIB, but with different critical indicators. The unifying fact is that almost all regulations in this area define the following list of tests: mechanical, electrical, chemical and environmental testing (water impact, ambient temperature, etc).

Unsolved aspects of the problem. Given the diversity of LIB [16] in its chemical composition, capacity and constant development of technology, it remains relevant to conduct research to determine the combustion temperature and secondary indicators, factors depending on the type of damage and the root cause of LIB burning. In the works cited above, the authors focus their attention directly on the combustion process and temperature indicators directly during the combustion of LIB. However, the issue of the cooling rate of LIB after combustion remains an urgent and unexplained problem, which after active combustion of LIB can remain a potential source of inflammation.

Having in mind the above material, the **purpose** of this work is to determine the nature and temperature of combustion LIB that is widely used as a battery for the car battery Tesla Model S, Model X 2015–2018 years of manufacturing. The difference between the technical parameters of this LIB from those presented in previous studies and the method of causing a short circuit of the LIB gives grounds to carry out a number of scientific experiments with subsequent determination of all possible combustion parameters and secondary indicators.

Problem statement and its mathematical model. According to [15], the first stage of the research was to determine the temperature of LIB combustion, their mass loss (after combustion) and to describe the nature of combustion after its mechanical damage (penetration) by a sharp object. To ensure the reliability of the results of the study and reduce the measurement error, it was assumed to repeat each of the stages of the study at least three times.

The most common format of LIB namely 18650 (Panasonic NCR18650B) to date, whose main component is lithium-nickel oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), was chosen as an object for further research. LIB was taken directly from the battery of the car Tesla Model S, the factory parameters of the battery are given in Table 1 [15, 16]. According to the manufacturer's characteristics [17], this LIB is a relatively new modification of the lithium-nickel oxide LIB on a new basis, which provides greater capacity and recharge cycles. At the same time, this LIB introduced a new solution to prevent overheating or short circuits, which can lead to its ignition.

Since, according to previous studies, it has been repeatedly confirmed that the most flammable are batteries that have a charge of more than 50 %, for the study, we select batteries with a charge of 100 % and a voltage of 4.2 volts.

The battery level will be achieved using a universal charger LiitoKala Lii-PD4 which allows you to "smart" charge LIB given its parameters and specifications, after charging the de-

Table 1

Parameters of the lithium-ion battery Panasonic NCR18650B

Parameter	Value
Diameter	18 mm
Length	65 mm
Voltage (rated)	3.6 V
Voltage (maximum)	4.2 V
Voltage (minimum)	2.5 V
Capacity (for temperatures +25 °C)	minimum – 3,250 mAh standard – 3,350 mAh
Weight	48.5 gram
Battery type	Tesla Custom Panasonic 18650 (analogue NCR18650B)

vice displays on a digital display all the main indicators of LIB (available voltage in the element, capacity). To verify the obtained values of the LIB voltage, the voltage was re-monitored using a Digital 266FT digital multimetre, the error of which is ±0.8 % when measuring DC current up to 1,000 V.

Six thermocouples were used to determine the temperature parameters of the LIB, complete with a secondary device-regulator-meter ПВІ-111, which allowed us to determine the temperature on the LIB case at four points (with simultaneous output of the obtained results on the PC, thermocouples Nos. 1–3, 5). At the same time, it was planned to determine the ambient temperature at a distance of 5 mm from the LIB during its combustion (thermocouples Nos. 6, 7). Additionally, the ambient temperature was recorded in the room where the study was conducted (thermocouples No. 4).

Thermocouples (chromel-alumel) make it possible to determine the temperature in the range of -50 to +1,200 °C, the layout of thermocouples on LIB is shown in Fig. 1.

In order to reduce the measurement error, simultaneously measurements of the battery case temperature were carried out by using a thermal imager camera (TIC) 3M SCOTT X380, which makes it possible to record temperature values in the range of –40 to +1,100 °C and record information for further analysis. Subsequently, the temperature indicators were compared with each other and summarized in a general table.

Mechanical damage of LIB was carried out using a nail with a length of 100 mm and a diameter of 3 mm, the applied force was about 5 kN [18], and the penetration duration was 0.01 seconds. According to the analysis of previous studies, the puncture of the battery was planned to occur in its central part.

According to the plan of experimental studies, four series of experiments were carried out, as a result of which, the temperature indicators of LIB combustion, duration of combustion, cooling duration to 50 °C and weight loss were determined.

The results of the experiment. Experimental studies were conducted on an average of +16 °C, atmospheric pressure of 96.8 kPa and relative humidity of 62 % using the equipment of a certified research laboratory of fire safety of Lviv State University of Life Safety.

Based on the results of the experiment and obtaining numerical values of temperature indicators, a graphical dependence was constructed to visually display the change in temperature over time. Fig. 3 presents temperature indicators of thermocouples 1–3 and 5.

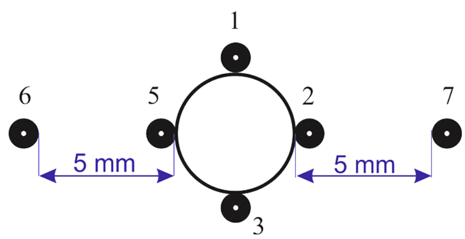

Fig. 1. The layout of thermocouples 1–7 on LIB

a *b*

Fig. 2. The process of penetrating LIB by nail

Besides, as a result of research, the temperature indicators of the environment (near-surface layer of LIB) were established at a distance of 5 mm from the case of LIB during its combustion depicted in Fig. 4.

Upon completion of the experimental part (combustion of elements) and complete cooling of the LIB to room temperature, there followed their control weighting. Initial and final weight indicators were summarized in Table 2 for further analysis.

Mathematical simulation. The obtained array of experimental measurements made it possible to construct a general dependence of the change in the temperature of the LIB case depends on time. In turn, the average values (from four points on the LIB case) showed a maximum temperature of 665 °C. The subsequent construction of the graphical dependence Fig. 5, of the temperature on the combustion time made it possible to establish the law of change in the LIB body temperature on time in the form of a polynomial dependence with the approximation coefficient $R^2 = 0.9988$.

$$T = 5 \cdot 10^{-15}\tau^6 - 2 \cdot 10^{-11}\tau^5 + 3 \cdot 10^{-8}\tau^4 - 2 \cdot 10^{-5}\tau^3 + 0.009\tau^2 - 2.8243\tau + 644.97,$$

where T is temperature, °C; τ is time, seconds.

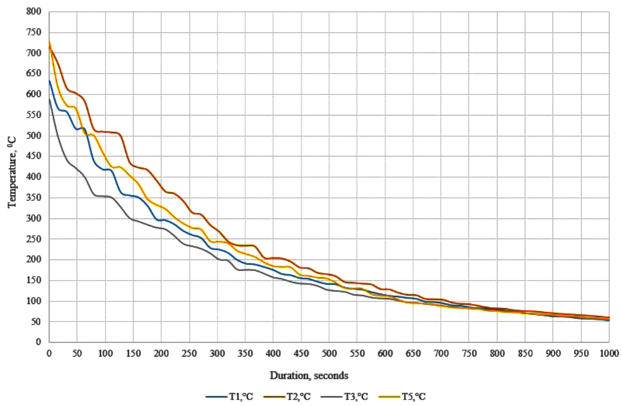

Fig. 3. Experimental values of temperature indicators of the LIB case during combustion

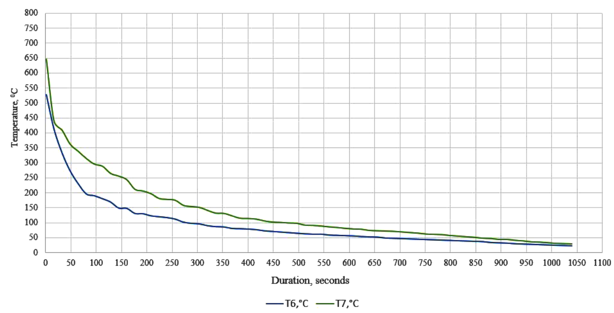

Fig. 4. Experimental values of temperature indicators at a distance of 5 mm from the LIB case during combustion

Table 2

Summary table of LIB weight before and after combustion

Item number	Starting weight, grams	Final weight, grams	Weight loss, grams
LIB No. 1	49.762	29.918	19.844
LIB No. 2	47.568	20.304	27.268
LIB No. 3	47.618	17.025	30.593
LIB No. 4	47.572	24.850	22.722
The average			25.106

The subsequent construction of the graphical dependence Fig. 6, made it possible to establish the law of change in ambient temperature (near-surface layer) from time in the form of a logarithmic dependence with an approximation coefficient equal to $R^2 = 0.9872$.

$$T = -88.4\ln(\tau) + 636.55, \quad \tau > 0.$$

In order to obtain a complete mathematical description of the cooling process of the LIB housing after combustion caused by the penetration of the housing, full-fledged mathematical modelling of the process was performed. To do this, it was necessary to find a solution to the differential equation of thermal conductivity

$$c\rho\frac{\partial t(r,\tau)}{\partial\tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda\frac{\partial t(r,\tau)}{\partial r}\right), \quad r \in [0, r_n], \quad \tau > 0, \tag{1}$$

with the following initial conditions, °C

$$t(r, 0) = t_0 = 650. \tag{2}$$

It was assumed that the heat exchange between the environment and the surface of the LIB occurs according to Newton-Richman's law.

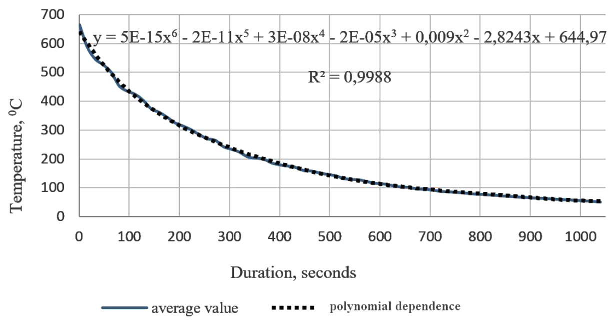

Fig. 5. Generalized temperature indicators on the LIB case and the superimposed trend line in the form of polynomial dependence

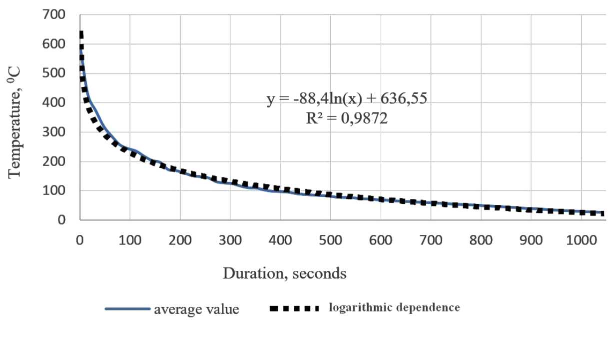

Fig. 6. Generalized temperature indicators at a distance of 5 mm from the LIB case and the superimposed trend line in the form of a logarithmic dependence

$$-\lambda\frac{\partial t}{\partial r}(r_n, \tau) = \alpha(t(r_n, \tau) - 650). \tag{3}$$

Taken into account, since LIB is a solid material, equation of symmetry must be added to (3)

$$\frac{\partial t}{\partial r}(0, \tau) = 0, \tag{4}$$

where $t(r, \tau)$ is temperature, °C; r is the radius, m; τ is duration, s.; c is specific heat capacity of a material, J/(kg · °C); ρ is material density, kg/m^3; λ is thermal conductivity of the material, W/(m · °C); α is heat transfer coefficient, W/(m^2 · °C).

The solution to this problem can be found in detail in [19, 20]. To solve the initial problem, the auxiliary problem of determining the distribution of a nonstationary temperature field in a multilayer hollow cylindrical structure of LIB with a "removed" cylinder of a sufficiently small radius is set in parallel. The symmetry condition (4) is replaced by the zero boundary condition of the second kind. The solution to the auxiliary problem is realized by applying the method of reduction using the concept of quasi-derivatives

$$t(r, \tau) = u(r, \tau) + v(r, \tau),$$

where, one of the functions ($u(r, \tau)$ or $v(r, \tau)$) is chosen in a special way, and the other is already defined unambiguously [20].

Finding the solution of functions $u(r, \tau)$ and $v(r, \tau)$ is implemented using the Fourier scheme and a modified method of eigenfunctions.

Using the results [19, 20], we determined that

$$\underline{u}(r, \tau) = 650,$$

and

$$v(r,\tau) = \sum_{k=1}^{\infty}\left[f_k \cdot e^{-\omega_k\tau} - \int_0^{\tau} e^{-\omega_k(\tau-s)}\gamma_k(s)ds\right] \cdot R_k(r,\omega_k).$$

Here f_k and γ_k are the corresponding coefficients of development of the initial condition and function $u(r, \tau)$ respectively in the Fourier series by the system of eigenfunctions $R_k(r, \omega_k)$, which are described in detail in the work [19].

To find the final solution to problems (3–6), the idea of a boundary transition is used, which consists in directing the radius of the removed cylinder to zero. This idea is described in detail in [20].

$$t(r,\tau) = \lim_{r_0\to 0}\left(u(r,\tau) + v(r,\tau)\right) = \lim_{r_0\to 0}$$
$$\left(650 + \sum_{i=0}^{n-1}\sum_{k=1}^{\infty}\left[f_{ki} \cdot e^{-\omega_k\tau} - \int_0^{\tau} e^{-\omega_k(\tau-s)}\gamma_{ki}(s)ds\right] \cdot R_{ki}(r,\omega_k)\theta_i\right). \tag{9}$$

It is established that with this approach all eigenfunctions of the corresponding problem have no singularities at zero, which means that the solutions of the original problem are limited in the whole construction.

The structure of the obtained explicit exact formulas allows you to quickly and efficiently calculate the distribution of the temperature field, which includes:

a) calculating the roots of the characteristic equation;

b) multiplication of a finite number of known matrices;

c) calculation of definite integrals;

d) summation of the required number of members of the series to obtain the specified accuracy of the calculation.

After performing the appropriate mathematical calculations, we obtain the result of the process of cooling the surface of the housing LIB from a temperature of 650 to 50 °C in comparison with the experimental data in the form of a graph presented in Fig. 4.

Given the graphical dependence presented (Fig. 7), it is seen that the results obtained by analytical formulas correlate

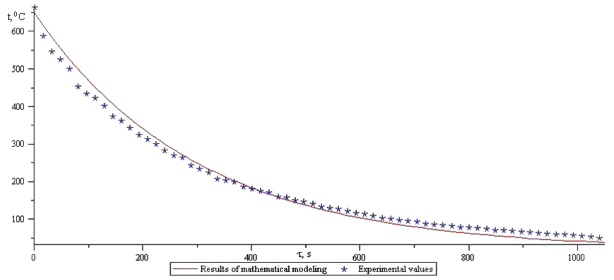

Fig. 7. Result of the process of cooling the surface of the housing LIB from a temperature of 650 to 50 °C in comparison with the experimental data in the form of a graph

well with the results of the experiment and can be the basis for further research.

Conclusions. Experimental studies showed that the maximum temperature on the LIB body reached 715 °C (on thermocouples 1, 2), and the minimum 587 °C (on thermocouple 3). After the LIB was damaged, there was an instantaneous release of heat and intense sparking for 2–4 seconds, after which there was open combustion with flashes of flame for up to 56–60 seconds.

During combustion, the LIB case became of hot yellow colour, which is indisputable evidence of high temperature. After completion of combustion, the duration of cooling the LIB case to a temperature of 50 °C was from 15 to 20 minutes, the average was 17 minutes.

After burning, the LIB case remained undamaged, Fig. 8, except for the hole formed after the nail penetration.

It was found that the maximum temperature recorded by thermocouples 6 and 7 at the time of ignition was 647 °C, and the average maximum value was 587 °C. The decrease in the temperature of the near-surface layer at a distance of 5 mm to 50 °C occurred in 13 minutes.

Analysis of the summary table of LIB weight loss showed that the weight loss of LIB after combustion is about 53–56 % of its initial weight, taking into account the study error obtained from the first LIB. Thus, in general, it can be argued that LIB lose about 53 % of the initial weight after full combustion because of nail penetration.

Further mathematical modelling of the cooling process of the LIB housing showed that the set mathematical problem and its further solution well describes this process (cooling), which correlates with the experimental values.

The obtained values and measurements can serve as a further scientific basis for the refinement and development of new recommendations for extinguishing vehicles operating from such LIB. In the future, the presented mathematical model can be used for analytical prediction of the cooling time of LIB, the possibility of heating other (adjacent) LIB to critical temperature, the possibility of ignition from overload, as it takes into account the geometric parameters of the element, without the need for experimental studies. The following studies can be aimed at determining the critical performance of the Panasonic NCR18650B in the case of its compression and the action of excess currents.

Fig. 8. LIB after conducting the experimental studies

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Експериментальна оцінка пожежної небезпеки літій-іонного елемента живлення під час його механічного пошкодження

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Мета. Експериментальне визначення температури горіння літій-іонного елементу живлення (ЛІЕЖ) унаслідок здійснення механічного пошкодження його корпусу шляхом побиття гострим предметом. Одночасно з тим, визначення часу охолодження літій-іонного елемента живлення після горіння й подальший математичний опис цього процесу.

Методика. Задля досягнення поставленої мети було підготовлено лабораторний стенд з відповідним вимірювальним обладнанням. Для математичного моделювання процесу охолодження були використані експериментальні значення й застосовані методи дослідження процесів теплообміну в багатошарових твердих суцільних циліндричних конструкціях.

Результати. Експериментальні дослідження показали, що максимальна температура на корпусі літій-іонного елемента живлення досягла 715 °С. У свою чергу середні значення показали температуру 665 °С. Середня тривалість охолодження до температури 50 °С становила не менше 17 хвилин. Дослідження втрати маси показали, що всі елементи після завершення згоряння втрачають близько 53 % початкової маси.

Наукова новизна. Уперше визначена температура горіння та час охолодження саме ЛІЕЖ Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$). Одночасно з експериментальними дослідженнями було проведене математичне моделювання процесу охолодження ЛІЕЖ із використанням теорії теплообміну. Установлено, що результати математичного моделювання добре корелюють з експериментальними значеннями. Такий підхід дає можливість, у подальшому, проводити аналітичні дослідження охолодження ЛІЕЖ без необхідності (де це можливо) проведення експериментів.

Практична значимість. Подальші впровадження й застосування отриманої математичної моделі надасть змогу здійснювати визначення часу охолодження, можливості нагрівання інших (суміжно розташованих) ЛІЕЖ до критичної температури, можливості загоряння від перенавантаження різноманітних ЛІЕЖ, використовуючи лише геометричні параметри без необхідності проведення експериментальних досліджень. Визначення часу охолодження ЛІЕЖ після горіння є цінним показником, оскільки дозволяє практично оцінити час, протягом якого ЛІЕЖ залишається потенційним джерелом небезпеки.

Ключові слова: *пожежна небезпека, температура горіння, літій-іонний елемент живлення, механічне проколювання*

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