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EXPERIMENTAL EVALUATION OF THE INFLUENCE OF EXCESSIVE ELECTRIC CURRENT ON THE FIRE HAZARD OF LITHIUM-ION POWER CELL

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Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) lithium-ion power cell (LIPC) and its performance after exposure to excess direct current are considered in this paper. The basic fire hazard indicators (element ignition temperature, flame temperature, element heating time, etc.) were experimentally established and mathematically confirmed for the examined LIPC.

According to the results of experimental studies, the time of occurrence of an irreversible thermochemical reaction in a lithium-ion power cell was determined depending on the different DC current strengths. Additionally, the critical temperature of the onset of an irreversible thermochemical reaction and the total combustion temperature of the element have been established. The application of the Joule-Lenz and Fourier laws allowed for a mathematical notation of the dependence (influence) of DC strength over time and the heating of the element to a critical temperature.

The heating time of Panasonic NCR18650B LIPC ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) to a critical temperature of 100–150 °C under the influence of excess current was experimentally established and mathematically confirmed.

The determined critical indicators of the element (temperature, time, etc.) make it possible to further devise a number of necessary regulatory documents that will allow them to be certified, tested, and, in general, to better understand the dangers that they may pose. A mathematical model was built, which, taking into account the geometrical parameters of the element, makes it possible to calculate the onset of the critical temperature of such elements with excellent geometric parameters without conducting experimental studies

Keywords: fire hazard, lithium-ion power cell, excess current, burning temperature

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1. Introduction

The price of petroleum products increases every year and it is generally expected that the price of oil will rise rapidly long before its reserves are exhausted. This is due to the fact that oil reserves will begin to decline, and its production will become a much more costly and complex process [1]. Given the global dependence on oil as an energy source, as well as the indisputable fact that oil is a limited resource, the world is facing a serious energy crisis. From year to year, various international organizations emphasize the need to change the general concept of energy supply in general and, in particular, the transportation sector. Such measures are aimed at reducing countries' dependence on suppliers of petroleum products and will significantly affect climate change associated with a constant increase in greenhouse gas emissions.

Lithium-ion power cells (LIPCs) are recognized as one of the best solutions of today in the concept of alternative energy sources [2]. In particular, they are an almost indispensable power cell capable of replacing traditional vehicles running on internal combustion engines. Modern alternatives to transport can be electric and hybrid cars, which gradually occupy leading positions in the world, electric scooters, hoverboards, electric bikes, etc. [3].

Despite the significant advantages of using LIPCs, there are increasing cases of self-ignition of LIPCs during their charging or even for no reason. Reports from various research organizations and scientific institutions suggest that the nature of the ignition of LIPCs, their extinguishing, and, especially, the causes of ignition are a complex and, at the same time, completely unexplored process. However, due to the rapid development of technologies and the variety of LIPCs, the relevance of some scientific research reported not so long ago is lost every year. That is why the study of new models of LIPCs, their characteristics, in particular fire hazards, under various working conditions, is a relevant scientific task. The solution to such problems will make it possible to further understand the scope and conditions of the possible use of certain LIPCs in everyday life, production, etc.

2. Literature review and problem statement

Most LIPCs are safe and reliable products. However, at the same time, LIPCs are quite unstable when they are in harsh and incorrect operating conditions, in particular, use over the regular period, electrical overload, overcharging, overheating, mechanical damage of various types [4]. Numerous studies [5, 6] show that even one LIPC can be a powerful source of thermal radiation and contribute to the spread of combustion. In fact, the main factor in the occurrence of burning LIPC is the occurrence of a short circuit in it, which can be caused by various factors [6]. The main causes of a short circuit can be direct mechanical damage (piercing of the element), deformation of the LIPC housing, and exposure to excessive currents. In particular, there are a number of standards [7], which regulate the procedure for conducting experimental studies to determine the critical indicators of LIPCs, subject to the influence of various critical factors of operation, before their widespread use. However, the constant process of improving the chemical composition of LIPCs, geometric dimensions requires additional research in this area [8]. Given that one of the reasons for the ignition of LIPC may be the supply of excessive current to it, which causes a critical increase in temperature and combustion, this issue remains relevant.

A significant amount of scientific research focused on determining the behavior of LIPC during the passage of excess currents through it, followed by the determination of temperature indicators and the construction of mathematical models of heating processes and the course of a thermochemical reaction. Thus, it is necessary to consider the main results from some of the most relevant scientific papers.

For example, in [9], a prismatic LIPC was considered and the effect of excess voltage on it was investigated. It has been established that the rate of heating of the surface of the element does not increase in proportion to the speed of the applied current. Also, during the study, the rate of destruction of the cathode and anode was established depending on the increase in the temperature of LIPS. Similar research objectives were set in [10] where the authors considered the prismatic $LiFePO_4$ LIPC with a capacity of 20 Am/h, used in modern electric cars. The study established the temperature indices of LIPC with excess current, the authors built a mathematical model of the process under study with the subsequent development of a 3D model for the distribution of temperature indicators during the charging of the element. The reported scientific findings are a thorough addition to the already existing results, but they do not shed light on the problem of ensuring fire safety of cylindrical LIPCs. First of all, this is due to the fact that the processes of heating prismatic and cylindrical LIPCs are described by different models of heat exchange processes.

Additional scientific contribution to research was made by the authors of work [11]. The researchers, similar to paper [10], looked at a prismatic-type LIPC with a total capacity of 35 Am/h ($LiMn_2O_4$) and investigated the distribution of the internal heating temperature, provided that excess currents were supplied to such LIPC. The conditions of different ambient temperatures of 30 and 60 °C were taken into account. The results of experimental studies made it possible to build a mathematical model for warming up such LIPCs using various methods and approaches. The works considered a high-capacity LIPC and, in their calculations, took into account excess currents of low power in the range of 1–5 A, which did not significantly affect their fire danger. The resulting mathematical models were calculated to determine only the parameters of the heating of the element to 80 °C, which does not significantly affect the onset of intense combustion of the element. Thus, in the cited works, the question of determining the fire hazard indicators of cylindrical 18650-format LIPCs remains unresolved.

In contrast to earlier studies reported in [12–15], there is a similar goal and task of research, however, already on cylindrical LIPCs. In particular, in work [12], the authors determined the value of radial thermal conductivity for 18650- and 26650-type LIPCs during their heating caused by electric current. It was experimentally found that the radial thermal conductivity of 18650 and 26650 LIPCs was derived from transient thermal measurements and is 0.43 ± 0.07 and 0.2 ± 0.04 W/m^{-1} K^{-1}, respectively. To obtain the specified values, the influence of different solid layers of LIPC (cathode, anode, and separator), as well as the interface between these layers, was taken into account.

In general, mathematical modeling of the process of heating LIPCs is a rather topical issue, which defies the only correct solution since it may involve the use of a variety of mathematical approaches and options for describing the process. In particular, in [13], a mathematical model of thermal heating of cylindrical 26650-format LIPCs ($LiFePO_4$) was developed. The mathematical model uses a polynomial approximation to estimate the radial temperature distribution in the middle of the LIPC under normal operating conditions. The adequacy and effectiveness of the proposed approach are verified on the basis of experimental data. The scientific result of work [13] aimed at determining the temperature distribution in a cylindrical LIPC does not in any way consider this element as a source of potential fire danger. The obtained results of mathematical modeling describe the process of heating an element under normal operating conditions, which makes it impossible to estimate the effect of excess currents at the time of the beginning of the occurrence of an irreversible thermochemical reaction in the element.

Considering LIPC as an element of a full-fledged battery of electric cars, the authors of [14] set the task to build a mathematical model for predicting the trend of heating a full-fledged battery. The paper considers cylindrical 18650-format LIPC ($LiNiCoMnO_2$, 2500 mAh). The resulting simplified mathematical model of battery heating made it possible to estimate the necessary parameters of the battery cooling system. Using the derived mathematical model, the best refrigerant of the three considered was experimentally established: air, dielectric oil, and perfluorinated polyester. Experimental results showed that the use of perfluorinated polyester allows one to keep the temperature of the battery within 48 °C, which is the best indicator compared to other substances. The results of the experiment also showed that under the estimated conditions, an air-cooling system requires between 100 and 1700 times more energy than other methods to maintain the same average temperature.

The results reported in [15] relate to the effect of discharge current on the process of thermal heating of 18650-format LIPC(CGR18650CG, manufactured by Panasonic, Japan) with the $Li(Ni_{0,33}Co_{0,33}Mn0_{,33})O_2$ cathode and graphite anode. In experimental studies, an external heat source with a power of 20 W and discharge currents from 1 to 6 A were used to simulate thermal load conditions under real working conditions. The results showed that the key parameters in assessing the process of occurrence of a thermochemical thermal reaction (weight loss, initial temperature indicators, etc.) are ultimately determined by the capacity of LIPC, and the discharge current is hardly of key importance. However, discharge currents can produce additional energy to speed up the process of thermal heating of an element. Compared to a battery in an open circuit of electric current, the start time of the thermochemical reaction of the element decreased by 7.4 % compared to LIPCs at a discharge of 6 A. To quantify the effect of the discharge current, the total heat generation by the discharge current was calculated. The results show that when the battery is discharged at 6 A, a heat of 1.6 kJ is released, which could heat the element to 34 °C. The cited study simulates the process of LIPC failure under a working condition, which is expected to help the safe use of LIPCs and increase the reliability of the control system of the battery of an electric car.

Although the above papers consider cylindrical 18650-format LIPCs, their scientific results do not reveal the prerequisites for the occurrence of combustion of such elements due to the influence of high-force direct current (10–30 A). Moreover, in [14, 15], elements with a cathode are considered, which in its chemical composition is different from $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, and such differences can have a significant impact on the final temperature indicators of combustion of the element, the time of the beginning of the occurrence of a thermochemical reaction. It should be noted separately that in work [15] either low-power currents (1–6 A) or a separate source of external heating were used as the initial source of element heating.

The scientific result of works [9–15] is the determination of temperature indicators of LIPCs, which do not significantly affect the onset of combustion of the element. In [9–15], the behavior of the Panasonic NCR18650B LIPC ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) under the influence of excess DC above 10 A was not considered.

One of the most common LIPCs used in electric cars is the Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), in particular its direct application in well-known Tesla electric cars. The use of this LIPC as an element of batteries of electric cars gives grounds to carry out scientific research in order to determine the critical factors and parameters that will affect the fire hazard during their operation.

3. The aim and objectives of the study

The aim of this study is to determine the patterns of fire hazard formation of Panasonic NCR18650B LIPC ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) under conditions of excess current. The obtained results of the study in practice, in the future, will provide an opportunity to carry out a reliable assessment of the causes and conditions of occurrence of fires caused by LIPCs of similar format and chemical composition.

To achieve the set aim, the following tasks have been solved:

– to conduct an experimental study to determine the time of heating of LIPCs at different current strengths until the occurrence of an irreversible thermochemical reaction and to establish the temperature indicators of its beginning;

– to build a mathematical model of the heating process of a cylindrical LIPC, taking into account its geometrical parameters and current-voltage characteristics of the current that caused the combustion of the element.

4. The study materials and methods

The object of research in this work is the Panasonic NCR18650B LIPC ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), produced in Japan. It is assumed that in the process of experimental research, direct current will be supplied to the LIPC, which will definitely affect the fire hazard of the element. Since it is the direct current that is used during the charging of LIPC, it will be appropriate to plan subsequent studies using this particular type of current.

In the work, we planned to carry out research at the empirical and theoretical levels. It was accepted that a number of experimental studies to determine the patterns of current exposure to fire hazard of LIPCs will not critically take into account the effect of ambient temperature on the potential result. During the mathematical modeling of the process of heating LIPCs to critical temperature indicators, the basics of the theory of heat transfer in multilayer continuous cylindrical bodies were used in the presence of an internal heat source. In this case, the heat source to be considered is the heat that is released during the flow of electric current into the LIPC.

After analyzing previous studies and determining the main parameters and characteristics necessary for control and fixation during experimental studies, the following version of the laboratory installation for the experiment was proposed, Fig. 1.

As a power source, a powerful Tesla transformer (produced in the PRC) was chosen, capable of supplying direct current with a stepwise increase in current strength from 15 to 200 A. In order to determine the exact current-voltage characteristics of the current, during the study, a voltmeter and the ammeter "Tense" (produced in Turkey) of direct current were connected to the laboratory installation. The specified devices are capable of determining the corresponding current parameters with an error of ±2 % and have a measurement range of 1–300 V and 0910 A, respectively.

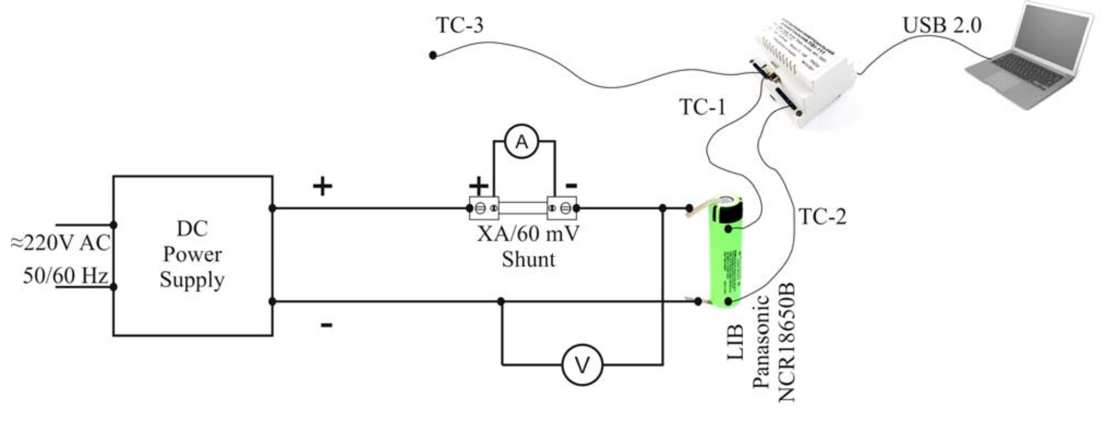

Fig. 1. Schematic of the laboratory bench for experimental research to determine the critical indicators of Panasonic NCR18650B LIPC under the influence of excess currents

The battery charge level will be achieved using the universal charger LiitoKala: Lii-PD4 (produced in the PRC), which allows for "smart" charging of LIPC, taking into account its parameters, chemical composition, and specification. After charging is complete, the device displays on the digital display all the main indicators of the LIPC (available voltage, capacity). For the reliability of the obtained data, voltage control will be repeatedly carried out using the Digital 266FT digital multimeter (produced in PRC), the error of which is ±0.8 % when measuring DC up to 1000 V.

To determine the temperature indicators of LIPC, the thermocouples chromel-alumel were used with the ability to register temperature indicators from –50 to 1200 °C. The acquisition of readings from thermocouples and their further processing will be provided by a secondary device-regulator-meter PVI-111 (Ukraine), which can simultaneously read and transmit information to a personal computer (PC) from 8 thermocouples. All temperature indicators will be recorded in real time on a PC to build graphic dependences, which will further facilitate the processing of research results. Directly during the experiment, thermocouples were fixed on both sides of the LIPC (on the "–" and "+" elements) while another thermocouple registered the ambient temperature.

According to previous studies [7], it is confirmed that the most fire hazardous are batteries that have a charge degree of more than 50 %. That is why in experimental studies only LIPCs with a charge degree of 100 % and a voltage of 4.2 volts were considered. Previously, each LIPC was soldered with electrical contacts for the convenience of their connection from a direct current source.

During the experiment, the current strength on the transformer unit changed in increments of 10 A, thus, a total of three types of loads, 20, 30, and 40 A, were applied. To ensure the determination of the reliability of the obtained research results and to reduce measurement error, each stage of the research was repeated 3–5 times.

5. The results of studies for determining the fire hazard associated with Panasonic NCR18650B exposed to the action of excess current

5. 1. Experimental studies to determine the critical indicators of Panasonic NCR18650B

The first results of experimental studies showed and confirmed the reliability of the structure of cylindrical 18650 LIPC due to the presence in the structure of the element of special protection against internal overheating of the element [16]. After applying current (17 A) to the LIPC, the internal temperature of the element increased to 80–104 °C. Due to the increase in the internal temperature of the element and the formation of excess gases, the LIPC safety valve (located on the "+" contact) is triggered, which breaks the electric circle, Fig. 2.

An interesting fact is that the temperature between the poles differs by 23 °C. This discrepancy confirms the fact that during the heating of the element, combustion products are formed, accumulating precisely near the safety valve. It is also worth noting that during the study, only 15 % of LIPC samples that participated in the study triggered protection. Further detailed analysis of LIPCs, in which the protection did not work, showed that due to minor corrosion of the elements, the emergency valve of LIPCs, which works as protection, was jammed. Thus, it can be argued that the presence of protection does not guarantee 100 % safety of LIPC if the internal temperature rises since improper storage conditions or other factors can affect the safety of the element and be the cause of fires [17]. To continue conducting experimental research in each LIPC where protection was triggered, manipulations were artificially carried out to restore its functioning.

In accordance with the research plan, a number of experimental studies were subsequently conducted, the results of which are given in Table 1.

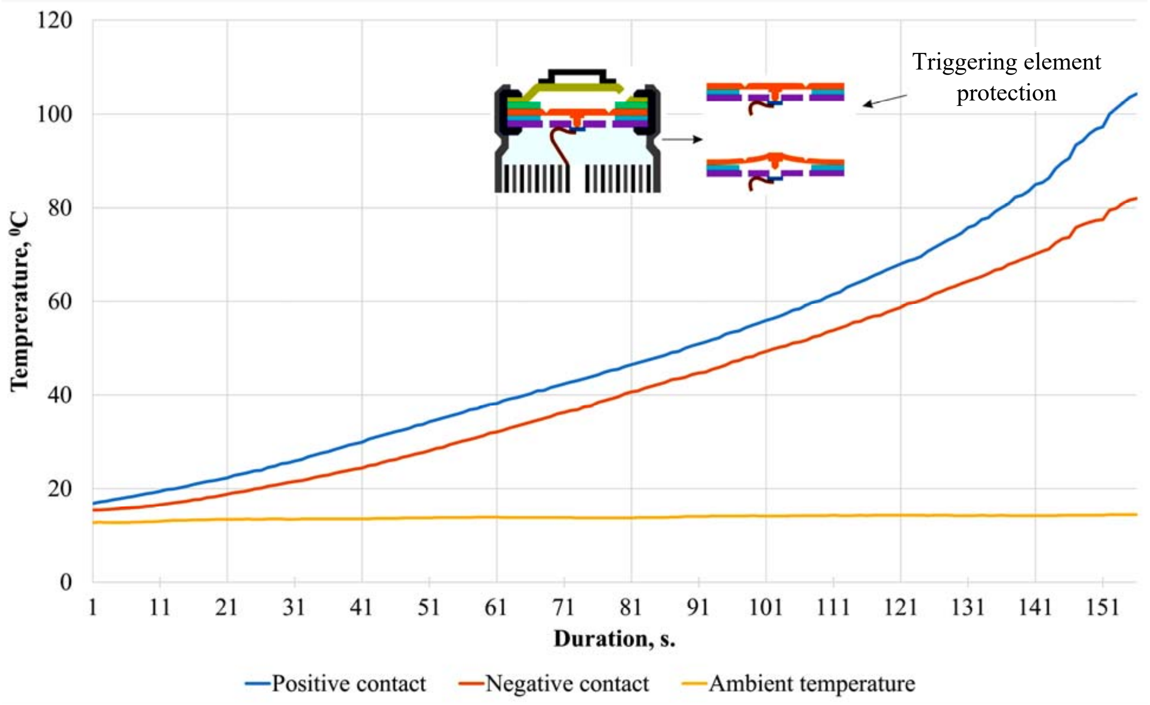

Fig. 2. Dependence of the protection response time on the Panasonic NCR18650B and the temperature distribution of the element at its different poles and a visual representation of the scheme of operation of the element safety valve

The nature of LIPC ignition during experimental studies and the appearance of samples after the research are shown in Fig. 3.

In order to display the results of the study better visually, we graphically show the results obtained on the example of a series of experiments with a current of 30 A.

When analyzing Fig. 4, it should be noted that in the range of 100–150 °C, an irreversible thermochemical reaction begins in LIPC. The occurrence of irreversible thermochemical processes causes the onset of intense combustion with an average flame temperature of 900–910 °C while the temperature of the element itself reaches 780–790 °C. The time of the onset of a thermochemical reaction is quite variable and, under the condition of a current of 17, 30, 40 A, is 117, 40, and 36 seconds, respectively.

In order to determine the dependence of the time of occurrence of an irreversible thermochemical reaction in LIPC more accurately depending on the current strength, a mathematical model of the investigated process was built.

a *b*

Fig. 3. Results of experimental studies to determine the critical indicators of Panasonic NCR18650B exposed to excess currents: *a* — the direct process of conducting experimental research; *b* — Panasonic NCR18650B after experimental research

Table 1

Results of experimental studies to determine the critical indicators of LIPCs exposed to excess currents

No.	Time, s	Temperature, °C	Note
17A*			
1	117	400–420	It threw up the middle (no burning)**
2	92	780–788	Burning brightly
3	115	360–367	It threw up one side (no burning)**
4	170	773–795	Burning brightly
5	86	786–790	Burning brightly
6	126	793–810	Burning brightly
Mean value, s		117	
30A			
1	40	400–420	It threw up the middle (no burning)**
2	51		It threw up the middle (no burning)**
3	60	786–790	Burning brightly
4	69		Burning brightly
5	53	360–367	It threw up the middle (no burning)**
6	38	786–790	Burning brightly
7	44	900–910	Burning (tore the case, flame on the thermocouple)
Mean value, s		50	
40A			
1	31	430–450	Non-intensive burning
2	42	780–790	Burning brightly
3	24	360–367	It threw up the middle (no burning)**
4	38	370–397	It threw up the middle (no burning)**
5	39	786–790	Burning brightly
6	30	806–820	Burning brightly
7	50	850–860	Burning brightly
Mean value, s		36	

*Note: * – the minimum value of the current that could be generated by the main power supply unit, taking into account the obtained ammeter indicators; ** – the wording "threw up the middle" means that the inner winding of the LIPC did not burn in the body of the element, and, under the influence of excessive internal pressure, flew out of the hull at a distance of up to 2 m*

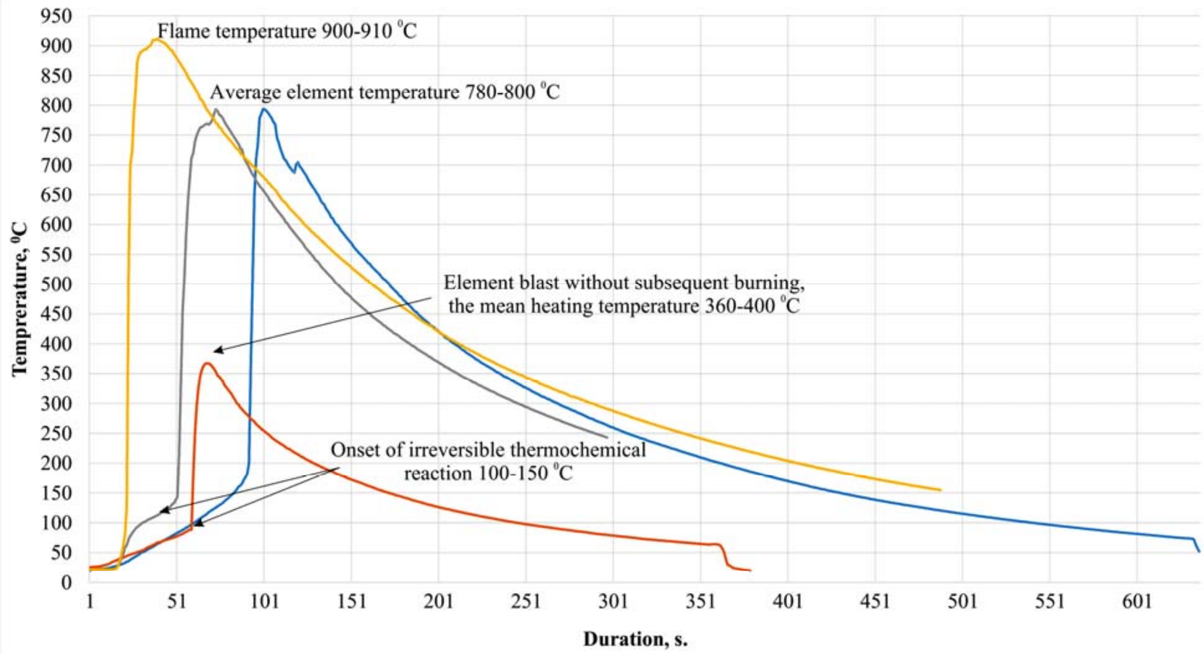

Fig. 4. Determination of critical indicators of Panasonic NCR18650B under the condition of a current of 30 A

5. 2. Mathematical modeling of Panasonic NCR18650B heating process caused by excess current

The process of heating the LIPC housing by connecting it to a source of electrical energy can be formulated as a mathematical model.

As is known from the Joule-Lenz law, when a current passes through a conductor, heat is released. In the theory of thermal conductivity, such heat generation is called an internal heat source. To this end, in order to simulate the process of heating LIPC due to the passage of electric current, it is necessary to find a solution to the differential equation of thermal conductivity with an internal heat source:

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

To determine the intensity of the internal heat source q_v that will be released due to the passage of electric current, we use the Joule-Lenz law:

$$Q=I^2R\tau, \qquad (2)$$

and applying Ohm's law to it, we obtain:

$$Q=IU\tau. \qquad (3)$$

On the other hand, in the middle of the volume of LIPC, the following amount of heat is released by the internal source q_v:

$$Q=q_vV\tau. \qquad (4)$$

By comparing equalities (3) and (4), we derive an equality to determine the intensity of the internal source:

$$IU\tau=q_vV\tau\Rightarrow q_v=\frac{IU}{\pi r_{\text{ліеж}}{}^2 l}.$$

Before turning on the electric current source, LIPC had a constant temperature, which means that the initial condition must be added to equation (1):

$$t=(r,0)=t_0=20\ ^\circ\text{C}. \qquad (5)$$

It was assumed that the heat transfer between the medium and the surface of the LIPC hull occurs according to the Newton-Richman heat transfer law, that is, the boundary conditions of the third kind are met:

$$-\lambda\frac{\partial t}{\partial r}(r_n,\tau)=\alpha\left(t(r_n,\tau)-20\right). \qquad (6)$$

Given that LIPC is a solid body, the symmetry condition must also be added to equation (1):

$$\frac{\partial t}{\partial r}(0,\tau)=0, \qquad (7)$$

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

The solution to the problem is studied in detail and described in [18, 19].

In order to solve the problem (1), (4) to (6) on heating the LIPC structure, a direct method for studying heat transfer processes using the idea of a boundary transition was used. The idea is to remove a cylinder of a sufficiently small radius from the middle of the structure and consider the mixed thermal conductivity problem in a multilayer hollow LIPC.

To this end, it is necessary to find a solution to the differential equation of thermal conductivity in a multilayer hollow structure with a boundary condition of the third kind (5) and a zero boundary condition of the second kind (6).

The solution to this problem was found using the reduction method

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

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 [19].

In [18], it is established that in any layer of LIPC, the function $u(r,\tau)$ is found from the formula

$$u_i(r,\tau)=(1,0)\cdot\mathbf{B}_i(r,r_i)\cdot\mathbf{B}(r_i,r_0)\cdot\mathbf{P}_0+$$
$$+\mathbf{B}_i(r,r_i)\cdot\sum_{k=1}^{i}\mathbf{B}(r_i,r_k)\cdot\mathbf{Z}_k+\int_{r_i}^{r}\mathbf{B}_i(r,s)\cdot\mathbf{q}_i(s)\mathrm{d}s,$$

where $\mathbf{P}_0$ is the initial vector, which is calculated from the formula

$$\mathbf{P}_0=\left(\mathbf{P}+\mathbf{QB}(r_n,r_0)\right)^{-1}\cdot\left(\Gamma-\mathbf{Q}\sum_{k=1}^{n}\mathbf{B}(r_n,r_k)\cdot Z_k\right).$$

Here P, Q, $\Gamma(\tau)$ – matrices and vector-function of boundary conditions; $\mathbf{B}_i$ – Cauchy matrix of the corresponding system of differential equations, to which the problem is reduced to determine the function $u(r,\tau)$; $\mathbf{Z}_k$ – vector-function of the intensity of internal heat sources.

$$P=\begin{pmatrix}0 & 1\\ 0 & 0\end{pmatrix},\quad Q=\begin{pmatrix}0 & 0\\ \alpha r_n & 1\end{pmatrix},\quad \Gamma(\tau)=\left(0,\alpha r_n\psi(\tau)\right)^T.$$

$$\mathbf{B}_i(r,s)=\begin{pmatrix}1 & K_i(r,s)\\ 0 & 1\end{pmatrix},\quad K_{1i}(r,s)=\frac{1}{\lambda_i}\ln\frac{r}{s},$$

$$\mathbf{B}(r_i,r_0)=\begin{pmatrix}1 & K(r_i,r_0)\\ 0 & 1\end{pmatrix},\quad K(r_i,r_0)=\sum_{k=0}^{i-1}\frac{1}{\lambda_k}\ln\frac{r_{k+1}}{r_k},$$

$$\mathbf{Z}_k=-\begin{pmatrix}\dfrac{q_{v,k-1}}{\lambda_{k-1}}\begin{bmatrix}\dfrac{1}{4}\left(r_k^2-r_{k-1}^2\right)-\\ -\dfrac{r_{k-1}^2}{2}\ln\dfrac{r_k}{r_{k-1}}\end{bmatrix}\\ \dfrac{q_{v,k-1}}{2}\left(r_k^2-r_{k-1}^2\right)\end{pmatrix}=\begin{pmatrix}z_k\\ z_k^{[1]}\end{pmatrix},\quad k=\overline{1,n-1},$$

$$\int_{r_i}^{r}\mathbf{B}_i(r,s)\mathbf{q}_i\mathrm{d}s=-\begin{pmatrix}\dfrac{q_{vi}}{\lambda_i}\begin{bmatrix}\dfrac{1}{4}\left(r^2-r_i^2\right)-\\ -\dfrac{r_i^2}{2}\ln\dfrac{r}{r_i}\end{bmatrix}\\ \dfrac{q_{vi}}{2}\left(r^2-r_i^2\right)\end{pmatrix},\quad i=\overline{0,n-1}.$$

Function $v(r,\tau)$ takes the following form:

$$v_i(r,\tau)=\sum_{k=1}^{\infty}\left[f_k\cdot e^{-\omega_k\tau}-\int_0^{\tau}e^{-\omega_k(\tau-s)}\gamma_k(s)\mathrm{d}s\right]\cdot R_{ki}(r,\omega_k),$$

where f_k and γ_k correspond to Fourier expansion coefficients, ω_k are eigenvalues, $R_k(r,\omega_k)$ are the corresponding eigenfunctions [19].

To find the solution to the original problem of heating LIPC, the idea of a boundary transition by directing the radius of the removed cylinder to zero was used. It is established [18] that with this approach all the corresponding functions have no features in zero, which means that the solutions to the original problem are limited throughout the entire structure.

Thus, based on the proposed mathematical model, it is possible to investigate the process of heating LIPC caused by excess current.

After performing the relevant mathematical calculations, taking into account the previously covered results of experimental studies [20, 21], a number of calculations were performed to determine the heating time of LIPC to a temperature of 100–150 °C for a current of 10 A, 17 A, 30 A, and 40 A at a voltage of 28 V. The results are shown in Fig. 5.

The value of the relative error δ of the occurrence of critical indicators of LIPC exposed to excess currents is determined from the formula

$$\delta = \frac{\tau_m - \tau_e}{\tau_m} \cdot 100\,\%,$$

where τ_m is the average value of the critical time determined by the calculation method (data from Fig. 5); τ_e is the average value of the critical time determined experimentally (data from Table 1).

The results of determining the relative error during the flow of current of 17 A, 30 A, and 40 A are given in Table 2.

Given the above (Table 2), it is clear that the results obtained using the proposed mathematical model are in convergence with those obtained experimentally.

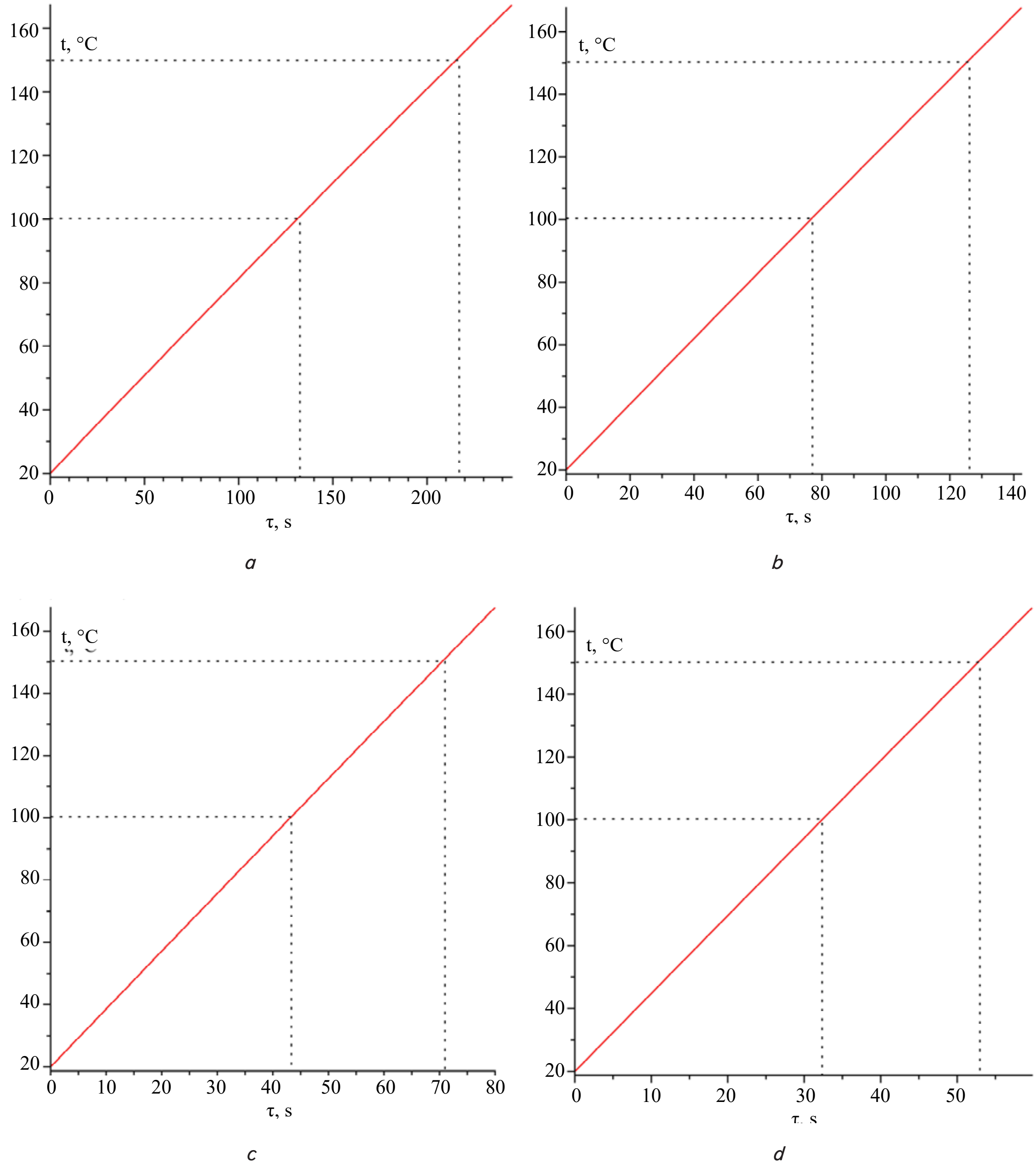

Fig. 5. Simulation of the heating process of Panasonic NCR18650B during current flow: *a* – 10 A; *b* – 17 A; *c* – 30 A; *d* – 40 A

Table 2

Comparative analysis of experimental and theoretical studies to determine the critical heating time of Panasonic NCR18650B under the condition of current and relative error of the obtained values

Current intensity, A	Average experimental value of time τ_e, s	Average calculated value of time τ_m, s	Relative error δ, %
17	117	102	14.71
30	50	57.5	13.04
40	36	42.5	15.29

Further mathematical modeling of the LIPC heating process showed that the time before the start of the increase in the temperature of LIPC to critical temperatures of 100–150 °C decreases with an increase in the current strength from 50 A. However, it then approaches a constant value within 5–10 seconds, which is a completely obvious result for the corresponding parameters of LIPCs.

6. Discussion of results of studying the effect of excess current on Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)

The final analysis of the results of experimental studies to determine the behavior characteristics of Panasonic NCR18650B LIPC under the condition of exposure to an increased current, shows that, first of all, each element behaves differently. All series of experimental studies confirm that the temperature indicators, the nature of combustion or destruction of LIPC are different from each other. However, due to the large number of conducted experimental studies, it is possible to single out and determine the averaged indicators. Another confirmation of this can be the derived mathematical model of the process of LIPC heating, which takes into account the current-voltage characteristics and geometric parameters of the element.

The general results of our experiments showed that in the end, after a certain period, exposed to the action of different current strengths, the LIPC ignited, burned intensively with the release of a significant number of sparks and flames for 2–3 seconds, Fig. 3. However, previous studies [6] did not sufficiently describe the process of the thermochemical reaction of LIPs due to the action of excess current. In particular, according to the results of research, it was established that in most cases there was a burnout of the inner shell of the element and a simultaneous “separation” of the surface element of the positive pole of the LIPC. In some cases, there was a rupture of the body of the LIPC and its subsequent combustion. However, in about 20 % of cases, LIPCs literally exploded without further combustion or with slight burning. It is also worth noting that there was a significant deformation of the battery housing, Fig. 3, which indicates a significant increase in pressure.

Our experimental studies, carried out to determine the fire hazard indicators of Panasonic NCR18650B, revealed the fact that the standard protection of such a LIPC may fail in the event of corrosion of the element. As a result of corrosion caused by violation of the rules of storage or operation of LIPC, deformation of the safety valve occurs, Fig. 2. This fact makes it impossible to disconnect the electric circuit in the event of an increase in the internal pressure of the element and leads to intensive burning of LIPCs. In particular, it was confirmed [16] that the standard protection of cylindrical LIPCs works in the range of 80–100 °C. However, it was established that the temperature indicators of the onset of an irreversible thermochemical reaction are somewhat different from those already known (90–130 °C) [6] and can vary between 100–150 °C, Fig. 4.

The temperature indicators of LIPCs confirmed that the average temperature of the element during combustion caused by overheating due to the action of excess current is in the range of 750–810 °C (Table 1). However, the flame temperature at the initial stage of combustion can reach more than 900 °C (Table 1). Despite the different chemical composition of LIPCs, such temperature indicators are reported in other studies [22], which once again confirms the reliability of the results obtained

The mathematically obtained time indicators of the heating rate of the inner shell of the LIPC clearly confirm the results of the experiments. The relative error of the average value of the time of the onset of combustion due to the action of increased current between experimental and mathematical calculations is 13–15 % (Table 2).

The experimental and mathematical results of research on determining the behavior of Panasonic NCR18650B LIPC under the condition of the action of an increased current on it fully determine its main indicators of fire hazard. The resulting mathematical model of LIPC heating, taking into account its main parameters, is a thorough addition to the already existing scientific studies involving similar LIPCs.

The proposed mathematical model of LIPC heating can also be used for other cylindrical LIPCs. However, it is necessary to take into account such parameters as internal resistance, geometric dimensions of the element, and the area of its internal cross-section. Given the chemical composition of the cathode of Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$), our results of experimental and analytical studies will be relevant only for LIPCs with a similar chemical composition.

Further scientific research may be aimed at establishing additional factors that may have an impact on the occurrence of combustion of such LIPCs. In particular, it is necessary to consider the behavior of Panasonic NCR18650B in the case of its direct mechanical damage (piercing of the hull) or deformation of the hull under the influence of an external source. Similar scientific studies are implied by a number of international standards [7], which precondition the issue of certification of LIPCs and determination of their fire hazard.

7. Conclusions

1. Due to the action of excess direct current on LIPC, it was experimentally found that the average start time of heating an element to a critical temperature of 100–150 °C is 117 seconds (at 17 A), 50 (at 30 A), 36 (at 40 A). The temperature of the element during combustion caused by excess current is 810 °C, and the flame temperature reaches 900 °C.

2. The derived mathematical model using the Joule-Lenz and Newton-Richman law, showing a discrepancy of 13–15 % of the experimental values, confirmed its adequacy. Thus, in the future, it makes it possible to calculate the heating time of the element at different current parameters and element sizes without the need for experimental research.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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EXPERIMENTAL EVALUATION OF THE INFLUENCE OF EXCESSIVE ELECTRIC CURRENT ON THE FIRE HAZARD OF LITHIUM-ION POWER CELL (p. 67–75)

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Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) lithium-ion power cell (LIPC) and its performance after exposure to excess direct current are considered in this paper. The basic fire hazard indicators (element ignition temperature, flame temperature, element heating time, etc.) were experimentally established and mathematically confirmed for the examined LIPC.

According to the results of experimental studies, the time of occurrence of an irreversible thermochemical reaction in a lithium-ion power cell was determined depending on the different DC current strengths. Additionally, the critical temperature of the onset of an irreversible thermochemical reaction and the total combustion temperature of the element have been established. The application of the Joule-Lenz and Fourier laws allowed for a mathematical notation of the dependence (influence) of DC strength over time and the heating of the element to a critical temperature.

The heating time of Panasonic NCR18650B LIPC ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) to a critical temperature of 100–150 °C under the influence of excess current was experimentally established and mathematically confirmed.

The determined critical indicators of the element (temperature, time, etc.) make it possible to further devise a number of necessary regulatory documents that will allow them to be certified, tested, and, in general, to better understand the dangers that they may pose. A mathematical model was built, which, taking into account the geometrical parameters of the element, makes it possible to calculate the onset of the critical temperature of such elements with excellent geometric parameters without conducting experimental studies.

Keywords: fire hazard, lithium-ion power cell, excess current, burning temperature.

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сосни, що вражена всиханням. Доведено, що в процесі усихання деревини знижується її пористість, а відповідно і межа міцності залежно від ступеня ураження грибом. А саме при площі пошкодження в межах 30–50 % межа міцності знижується понад 1,3 рази, а при ураженні грибом площі в межах 80÷100 % деревина стає м'якшою, більш пластичною, при цьому межа міцності знижується в 1,1 рази. На основі одержаних результатів фізико-хімічних досліджень виявлені розбіжності в ІЧ-спектрах, що вказують на структурні зміни в складових компонентів деревини. Спостерігається зниження або відсутність інтенсивностей смуг поглинання одних функціональних груп та з›явлення або інтенсифікація інших. Зразки деревини при визначенні вищої теплоти згоряння показують різницю у значеннях, що пояснюється структурними змінами у компонентах деревини, викликаних біологічними процесами. Дані термогравіметричного аналізу вказують на повне вигоряння сухостійної деревини сосни. Але для деревини із неослаблених усиханням деревостанів, коксовий залишок вигоряє при вищій температурі. Уражена мікроорганізмами деревина з синьою пігментацією має суттєві відмінності в області нагрівання 400÷700 °С. Характер вигоряння коксового дозволяє зробити припущення щодо різного за якісним і кількісним складом коксового залишку, який утворюється завдяки структурним змінам. Практична цінність полягає у тому, що отримані результати визначення властивостей та структури сухостійної деревини, уможливлюють встановити умови експлуатації виробів і будівельних конструкцій.

Ключові слова: деревина сосни, сухостійна деревина, межа міцності, зміна структури деревини, ураження мікроорганізмами.

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ЕМПІРИЧНА КУМУЛЯТИВНА ФУНКЦІЯ РОЗПОДІЛУ ХАРАКТЕРНОЇ ОЗНАКИ ГАЗОВОГО СЕРЕДОВИЩА ПРИ ЗАГОРЯННЯХ (с. 60–66)

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Об'єктом дослідження є динаміка характерної ознаки прирощення стану газового середовища в приміщенні при появі теплового джерела пожежі. Предметом дослідження є вид емпіричної кумулятивної функції розподілу динаміки характерної ознаки прирощення стану газового середовища за відсутності та появі теплового джерела пожежі в приміщенні. У якості характерної ознаки обрано ймовірність нерекурентності прирощень вектору станів газового середовища. Результати дослідження дозволяють оперативно виявляти теплові джерела пожежі у невизначених умовах. Обґрунтовано методику дослідження емпіричної кумулятивної функції розподілу динаміки ймовірності нерекурентності прирощень вектора стану газового середовища. Методика включає виконання семи послідовних процедур і дозволяє досліджувати зазначену функцію для довільних інтервалах часу. Досліджено емпіричну кумулятивну функцію розподілу для двох фіксованих інтервалів часу рівної тривалості до і після появи тестових теплових джерел пожежі у лабораторній камері. Встановлено, що особливості емпіричних кумулятивних функцій розподілу динаміки ймовірності нерекурентності прирощень вектора стану газового середовища дозволяють здійснювати раннє виявлення пожежі. Головною ознакою виявлення є зниження фіксованих значень емпіричної кумулятивної функції розподілу. Для тестових теплових джерел фіксовані значення емпіричної кумулятивної функції розподілу лежать в діапазоні 0,15–0,44. Дані ймовірності обумовлюються різною швидкістю займання тестових теплових джерел. Результати досліджень свідчать про можливість використання виявлених особливостей емпіричних кумулятивних функцій розподілу динаміки ймовірності нерекурентності прирощень вектора стану газового середовища для раннього виявлення загорянь.

Ключові слова: газове середовище, динаміка прирощень станів, теплові джерела пожежі, емпірична кумулятивна функція розподілу.

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ЕКСПЕРИМЕНТАЛЬНА ОЦІНКА ВПЛИВУ НАДЛИШКОВОГО ЕЛЕКТРИЧНОГО СТРУМУ НА ПОЖЕЖНУ НЕБЕЗПЕКУ ЛІТІЙ-ІОННОГО ЕЛЕМЕНТА ЖИВЛЕННЯ (с. 67–75)

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Було розглянуто літій-іонний елемент живлення (ЛІЕЖ) Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) та його поведінку внаслідок дії на нього надлишкового постійного струму. Експериментально було встановлено та математично підтверджено основні пожежонебезпечні показники (температуру горіння елементу, температуру полум'я, час нагрівання елемента, тощо) представленого ЛІЕЖ.

За результатами експериментальних досліджень було визначено час настання незворотної термохімічної реакції в літій-іонному елементі живлення залежно від різної сили постійного струму. Додатково, встановлено критичну температуру початку незворотної термохімічної реакції та загальну температуру горіння елементу. Застосування законів Джоуля-Ленца та Фур'є дало змогу здійснити математичний опис залежності (впливу) сили постійного струму в часі та нагрівання елемента до критичної температури.

Експериментально встановлено та математично підтверджено час нагріву ЛІЕЖ Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) до критичної температури 100–150 °С за умови впливу надлишкового струму. Встановлено, що середній час початку горіння ЛІЕЖ при 17, 30, 40 А становить 103, 58, 43 секунд відповідно.

Встановленні критичні показники елементу (температура, час, тощо) дають можливість в подальшому здійснити розробку низки необхідних регулюючих документів, що наддадуть змогу здійснювати їх сертифікацію, апробацію та загалом краще зрозуміти небезпеки, які вони можуть представляти. Отримана математична модель, яка, враховуючи геометричні параметри елементу, дає можливість здійснити розрахунок настання критичної температури подібних елементів з відмінними геометричними параметрами без проведення експериментальних досліджень.

Ключові слова: пожежна небезпека, літій-іонний елемент живлення, надлишковий струм, температура горіння.