PROCEEDINGS OF THE LATVIAN ACADEMY OF SCIENCES. Section B,
Vol. 78 (2024), No. 5/6 (752/753), pp. 372–379.

DOI: 10.2478/prolas-2024-0047

Original Paper

DETERMINATION OF THERMAL PHYSICAL CHARACTERISTICS OF THE PANASONIC NCR18650B LITHIUM-ION POWER SUPPLY ELEMENT

Oleksandr Lazarenko[#], Oleg Pazen, Yarema Velykyi, Ruslan Parkhomenko, and Yurii Stepaniak

Lviv State University of Life Safety, 25 Kleparivska Str., Lviv, 79007, UKRAINE

[#] Corresponding author, o.lazarenko@ldubgd.edu.ua

Communicated by Andris Ozols

The purpose of the work was to determine the thermophysical characteristics of Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) batteries under the condition of an external heating source. Obtaining the appropriate thermophysical characteristics of lithium-ion battery (LIB) cells can be confirmed by experimental studies and mathematical calculations. Obtaining relevant results in the future makes it possible to carry out a professional assessment of the heating temperature of such LIB, the conditions of their combustion, and the spread of fire in general. According to the results of experimental studies, namely, under the condition of the action of an external source of high temperature (flame) and uniform heating of the outer walls of the LIB, its inner part is heated to an average temperature of 168 °C for 70 seconds. For comparison, the corresponding temperature in the middle of the LIB without internal filling (cathode and anode) is reached within 45 seconds. The developed mathematical model based on the differential equation of thermal conductivity in the cylindrical coordinate system and the use of the Newton-Richmann`s Law of Heat Exchange made it possible to carry out mathematical modelling of the heating process of a LIB. Further comparison of the experimental values with the mathematical model confirmed the correctness of the experiment. The obtained mathematical model based on the experimental values made it possible to obtain the corresponding numerical values of the specific heat capacity, material density, thermal conductivity coefficient and heat exchange between the surface and the near-surface layer of the Panasonic NCR18650B.

Keywords: *thermal conductivity, thermophysical characteristics, mathematical model, fire hazard, electric car battery.*

INTRODUCTION

Annual global statistics on the sale and use of vehicles show unceasing growth by all possible indicators (Zhang *et al.*, 2022). A similar situation is observed in the field of vehicles using alternative energy sources, in particular electric vehicles (Domarch and Chrechi, 2023). At the same time, research organisations collect statistical data on the causes and consequences of fires in electric vehicles. Accordingly (EV fires…, 2023), about 455 cases of electric cars catching fire have been recorded to date. The main cause of electric vehicle fires is mechanical damage to the battery, which consists of lithium-ion battery (LIB) power cells. In addition, it was established that most often, it is Tesla cars that suffer from cases of battery damage and, as a result, subsequent fires. Returning to the statistical data and analysis of the reasons for the ignition of electric vehicle batteries, the influence of an external source of ignition (fire) is noted in fourth place, which leads to the occurrence of an irreversible thermochemical reaction in the battery and its subsequent combustion. In general, it has been confirmed that an increase in the internal temperature of the LIB to 160–170 °C leads to further thermal decomposition of the element and its combustion. Numerous studies (Lee *et al.*, 2020; Sun *et al*., 2020; Liu *et al*., 2021) have established and shown the immediate hazards and specifics of LIB burning. Today, more and more countries and emergency rescue agencies are developing procedures for responding to and eliminating the consequences of fires at the LIB (Parkhomenko *et al*., 2023). Such data testify to the real danger and relevance of this line of research.

The continuation of the creation of a scientifically based basis for determining the features, methods, means and causes of the occurrence of thermochemical reactions in LIB is an actual scientific direction of research. This is especially relevant, taking into account the constant change in the chemical composition and type of LIB used by humans. At the same time, the deepening of knowledge about the fire danger of LIB will allow formation of a national strategy for the development, operation and use of vehicles on alternative energy sources.

The definition of the fire hazard of the Panasonic NCR18650B LIB by Ruiza *et al.,* (2018) can be conventionally divided into several options: mechanical damage to the LIB housing (piercing by a sharp object, deformation of the housing of the element (Lazarenko *et al.,* 2022; 2023), and the effects of excessive current (Lazarenko *et al.,* 2022). Experimental and analytical studies have shown that the greatest fire hazard of LIB Panasonic NCR18650B is caused by the action of excessive current, which is accompanied by heating to a temperature of about 800 °C.

Analysing modern achievements in the direction of determining and establishing thermophysical characteristics of LIB, it is necessary to note and highlight the following scientifically based results.

Previous work (Li *et al*., 2017) showed that it is possible to use infrared imaging technology to study the temperature distribution of $Li(NiCoMn)O_2$ prismatic LIB in natural convection conditions. In that study, it was established that the positive electrode shows a higher rate of heat release than that of the negative electrode. In addition, the dependence of the temperature distribution on the LIB area, depending on the placement of the current receivers, was established. The established difference in temperature can reach 51%.

Another study (Xie *et al*., 2018) provides an important scientific basis for the technology of monitoring and controlling the temperature of LIB used in electric vehicle batteries. During the study, the authors took into account thermal conductivity and convection under the conditions of normal use of vehicles. It was established that battery heating is related to the temperature coefficient of the electromotive force, the degree of charge of the LIB, the battery resistance, and the current coefficient. Based on the experiment, the important characteristics of LIB at different ambient temperatures (25 ^{o}C, 0 ^{o}C and 40 ^{o}C) were studied.

Experimental studies (Hoelle *et al.,* 2021) have also aimed to describe the thermochemical reaction in the prismatic-type LIB due to piercing of the case. In total, the study used 50 prismatic LIBs of 25 different versions with a capacity from 8 to 145 A/h. The work highlights such important experimental results as mass loss, the volume of released gas and heat, depending on the capacity of the LIB.

The results of the study were compared with already existing studies, in particular with (Golubkov *et al*., 2014), where the researchers determined similar parameters, but regarding the cylindrical 18650 format LIB and under the condition of its overheating in a special furnace. The LIB sample was slowly heated, starting at 25 °C, with a heating rate of ~2 °C min^{-1}. After reaching 220 °C, a thermochemical reaction followed by combustion took place in the LIB. The temperature of the LIB rose from 220 °C to 687 °C in a few seconds.

These studies (Golubkov *et al*., 2014; Hoelle *et al.,* 2021) were continued (Weber *et al*., 2023), where the thermochemical decomposition was developed based on ten chemical decomposition reactions. Accordingly, a combination of chemical models with mathematical modelling of thermal decomposition was carried out for further forecasting of temperature curves, as well as the amount and composition of gases released during the burning of LIB. The research was carried out on a batch LIB. The experimental results were confirmed by mathematical calculations and showed that upon reaching the temperature limit in the range of 210–214 °C within 45–50 s. there was direct self-ignition of the LIB and release of combustion products. At the same time, the paper presented and determines the thermophysical parameters of the studied LIB.

Other work (Dong *et al*., 2023) gave additional results on the danger of LIB under the condition of mechanical damage. In the study, the authors considered a $Li(Ni_{0.7}Co_{0.2}Mn_{0.1})O_2$ (NCM 721) batch battery with a capacity of 52 A/h and measured the temperature of its surface and in the middle of the element during a thermochemical reaction as a result of mechanical damage or excessive current. According to the results of several experimental studies, it was established that the average maximum temperature of the surface of LIB was 835–925 °C. In addition, it was established that within 29 seconds from the beginning of mechanical damage, the destruction of the LIB occurred with the release of gases and flames. As a limitation of this study, it should be noted that the work considered a completely different type of LIB and, in general, did not establish the thermophysical characteristics of the studied LIB.

Structural changes in the internal content of the battery material and temperature in various parts of the battery during the process of the thermochemical reaction have been determined (Liang *et al*., 2023). The study showed that at a furnace temperature of 135°C~195°C (in which the LIB was heated), the maximum temperature during the thermochemical reaction of the LIB reached approximately 625 °C. It was established that increasing the battery charge level leads to an earlier onset of the thermochemical reaction. In addition, an increase in the LIB heat transfer coefficient leads to an earlier onset of the thermochemical reaction. Modelling and analysis of characteristics were carried out in a prismatic LIB NCM523. In addition, it was established that the use of appropriate cooling methods (liquid cooling or direct cooling) can prevent, to some extent, the occurrence of the thermochemical reaction phenomenon.

Another study (Tan *et al.*, 2024) focused on the 26,650 LIB format and the study of the amount of heat released by the element during charge and discharge cycles. In this study, a two-dimensional axisymmetric model of electrochemical-thermal communication was developed, which was then verified using experimental data. In addition, factors such as ambient temperature, reaction heat, ohmic heat, and polarisation heat were separately taken into account. The quantitative results showed that the total heat released in the continuous discharge process was the highest. The maximum amount of heat per unit volume was 67,446.99 W/m^3 at a temperature factor of 2C multiplier discharge. The thermophysical characteristics of the LIB format 26 650 (NMC lithium-polymer) were taken into account for the development of the mathematical model.

Taking into account the interest of the scientific community in researching and determining the temperature of LIB, in the study a flame retardant composite material with a phase change (CPCM) consisting of paraffin, high-density polyethene, foamed graphite, ammonium polyphosphate, red phosphorus and zinc oxide was proposed (Yu *et al.*, 2023). The effectiveness of the coating under the condition of different ratios of flame retardants was investigated, and their effectiveness was compared. The experimental studies showed that the maximum temperature of the LIB (Sanyo NCR18650GA format 18650) was 50 ^{o}C at a discharge rate of 2C and that the temperature difference could be controlled within 5C;

The temperature profile of LIB as an indicator of the ageing state of LIB has been determined (Kozma *et al.*, 2023). The authors proposed a method capable of detecting changes in the internal electrical resistance of the battery due to ageing based on calorimetric measurements. This method of diagnosing ageing is based on measuring the surface temperature using thermocouples. A comparison of the heat produced by calorimetric and electrical methods was also carried out, which made it possible to determine the accuracy of the obtained measurement results. The difference obtained was less than 10%, indicating good agreement between the two methods.

Based on the previous research in the direction of determining temperature and establishing thermophysical characteristics of LIB, the following conclusions can be drawn:

– the vast majority of research has been focused on the issue of establishing the temperature of prismatic-format LIB in the conditions of everyday operation or stimulating the occurrence of a thermochemical reaction;

– determination of the temperature of LIB was carried out to establish the dependence of the degree of discharge of the element or the conditions of its reliable and stable operation in the range of 30–60 °C without taking into account external factors;

– setting the temperature of LIB was carried out on the surface of the element;

– defined thermophysical characteristics of LIB refer to individual types of LIB with individual chemical composition.

Further research on the issue of determining the thermophysical characteristics of LIBs can become a scientific basis for the development of protection systems directly for storage batteries, in particular electric vehicles, and not only in the event of an external energy source (combustion). Obtaining scientifically based parameters of thermophysical characteristics will also allow us to carry out a forecasted assessment of the spread of burning in LIB under appropriate conditions. Thus, the establishment of the thermophysical characteristics of a cylindrical LIB under the condition of the action of an external heating source remains an actual scientific task that requires further determination.

The purpose of the study was to determine the thermophysical characteristics of Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) batteries under the condition of an external heating source. Obtaining the appropriate thermophysical characteristics of LIB, confirmed by experimental research and mathematical calculation, would in the future, make it possible to carry out a professional assessment of the heating temperature of such LIB and the conditions for their combustion and fire spread as a whole.

To achieve the goal of the research, the following tasks were defined:

– to carry out an experimental study to establish the warm-up time and temperature in the middle of the LIB during the action of a third-party heating source;

– to develop a mathematical model of the process of temperature growth in the middle of LIB under the condition of the action of a third-party heating source;

– to establish the thermophysical characteristics of the Panasonic NCR18650B LIB necessary for further use and forecasting the temperature rise in similar LIB.

MATERIALS AND METHODS

The main hypothesis of the study was that the Japanese-made Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) LIB has significant fire hazard if it is exposed to an external source of thermal radiation (flame), which causes an increase in the internal temperature and the subsequent occurrence of an irreversible thermochemical reaction with subsequent combustion of the element. Accordingly, Panasonic

NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) LIB was selected as the research object.

We determined the warm-up time and the temperature in the middle of the LIB during the action of an external source of thermal radiation. To obtain more experimental data, the study was divided into two stages, namely:

1. Determination of temperature in the LIB housing without internal filling;

2. Determination of temperature in the middle of a full-fledged LIB with internal filling.

Conducting experimental studies in two stages allowed to compare the obtained experimental data on the heating of LIB for different physical parameters of the element itself.

Thus, a 100% discharged Panasonic NCR18650B sample was prepared for research. Accordingly, a completely fire-resistant element with an internal filling corresponding to the working sample was obtained. After that, in the experimentally prepared sample, a through-hole with a diameter of 2 mm was drilled along its entire length for further placement of thermocouples (Fig. 1a). Also, the LIB case without internal filling was prepared separately (Fig. 1 b), that is, the entire internal winding (cathode and anode) was previously removed. Later, thermocouples were also placed in the middle of the empty body of the element.

Determination of temperature change was carried out throughout the experiment at the expense of chrome-alumni thermocouples with the possibility of fixing temperature from –50 to 1200 °C. Recording of indicators from thermocouples and their further processing was ensured by the secondary device PVI-111 regulator-determinator (Ukraine), which can simultaneously read and transmit information to a personal computer (PC) from 8 thermocouples. The device allows you to read temperature in real-time with an interval of 1 second under environmental conditions from –10 to +50 °C. Thermocouples were placed directly in the middle of the LIB two pieces each, as well as on the surface of the element in the amount of two pieces.

The laboratory stands for heating the LIB from an external source of thermal radiation (flame) and subsequent fixation of temperature is presented in Figure 2.

The source of open combustion (flame) was two gas burners fed from a gas cylinder. To ensure uniform heating of the entire area of LIB, the element itself was placed in an additional metal case, and burners carried out primary heating of the metal case, which created the effect of an “oven”. The flame temperature of the gas burner was 750 °C. Thermocouples TC-1 and TC-2 were placed directly in the middle of the LIB, and TC-3 and TC-4 on the surface of the element. The LIB itself was attached to a tripod with the help of special fasteners.

The element was heated up to reach 170–250 °C in the middle of the LIB. Given that the occurrence of a thermochemical reaction in the element begins when the temperature index reaches 170 °C, there is no need to warm it up. However, to verify the impossibility of LIB ignition at 100% discharge and reaching an internal temperature above 170 °C, heating of the element continued to a temperature of 250 °C (±30 °C).

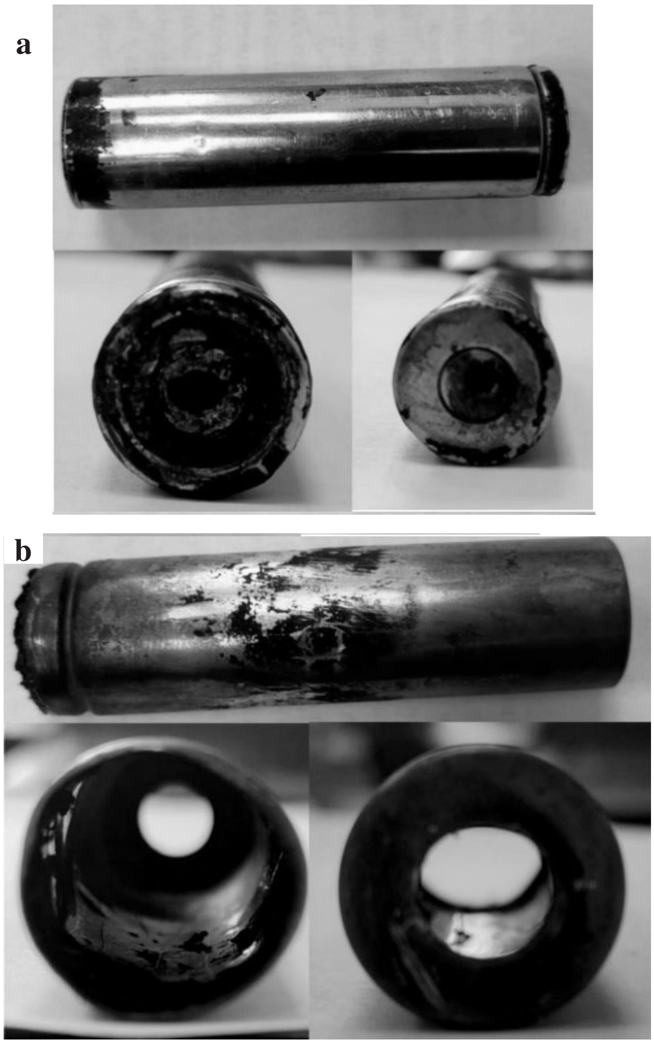

Fig. 1. Panasonic NCR1865 lithium-ion battery sample: **a**, with internal filling and holes for placing thermocouples; **b**, Panasonic NCR18650B metal case without internal filling.

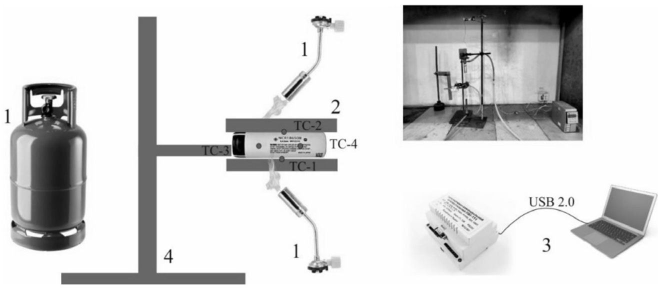

Fig. 2. Scheme of a laboratory bench for heating the Panasonic NCR18650B from an external source (flame) and further determination of the temperature by the chrome-alumni thermocouples: **1**, burners with a gas cylinders; **2**, additional metal case for placing Panasonic NCR18650B; **3**, PVI-111 with thermocouples (TC-1, TC-2, TC-3, TC-4); **4**, tripod for fixing the element.

RESULTS

Firstly, the temperature parameters of heating the empty body of the LIB were determined (Fig. 3). The total duration of the first stage of experimental research was 74 seconds. Starting from the 16^{th} second of the experiment, an increase in the temperature on the surface of the LIB was recorded within the range of 35–40 °C, while the average temperature in the middle of the LIB body was 27.7 °C. The surface temperature of the LIB hull at 40-45 seconds of the experiment was 170–195 °C, while the internal temperature in the middle of the hollow LIB hull was 133–165 °C. In general, the general equilibration of temperature on the surface and in the middle of the LIB within 210 °C was observed at 51 seconds of the first stage of experimental research (Fig. 3).

In the second stage of experimental research results were obtained on heating of a full-fledged LIB (Fig. 4). During the experiment, thermocouple T3 significantly deviated from the general temperature indicator on the surface of the LIB due to too close contact with the flame of the gas burner. Thus, its indicators can be considered false and were not taken into account during the analysis of the research results. However, the general temperature of the surface of LIB can be compared with the results of the first stage of the study (Fig. 3).

The total duration of the second stage of experimental research lasted about 98 seconds, taking into account the maximum heating of the element to a temperature of 316 °C. At the same time, it is worth noting that the surface temperature of the element did not balance with the internal temperature and was 385 °C on average. Starting from the 23^{rd} second of the experiment, an increase in temperature in the middle of the LIB was recorded in the range of 47–50 °C, while the average temperature on the surface of the LIB was 120 °C. At 70 seconds, the temperature of the surface of the LIB hull was 266 °C, while the internal temperature in the middle of the hollow LIB hull was 166–171 °C. In general, LIB heated up to a temperature of 364 °C for 128 seconds, but the element did not burn.

Mathematical modelling of the heating of the inner shell of the Panasonic NCR18650B under the condition of the action of an external source of thermal radiation (flame)

To obtain a complete mathematical description of the process of heating the inner shell of the Panasonic NCR18650B under the condition of a heat source, mathematical modelling of this process was carried out. Since this power element is a continuous cylindrical body, it was necessary to find a solution to the differential equation of thermal conductivity in a cylindrical coordinate system:

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

To find the solution of equation (1), it is necessary to add an initial condition. Since the ambient temperature before the start of the experimental test was equal to the temperature

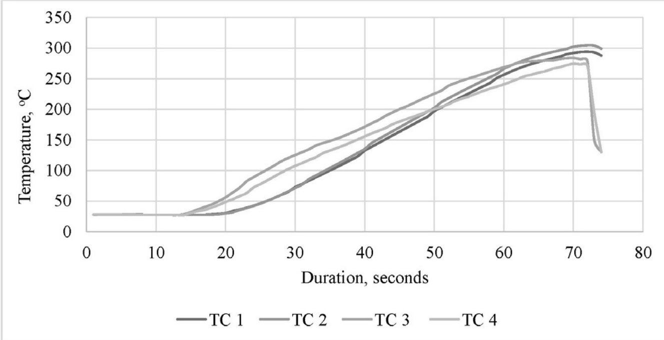

Fig. 3. The results of determining the temperature of the Panasonic NCR18650B case heating, from an external source (flame): TC 1, TC 2, thermocouples in the middle of the LIB; TC 3, TC 4, thermocouples on the surface of LIB.

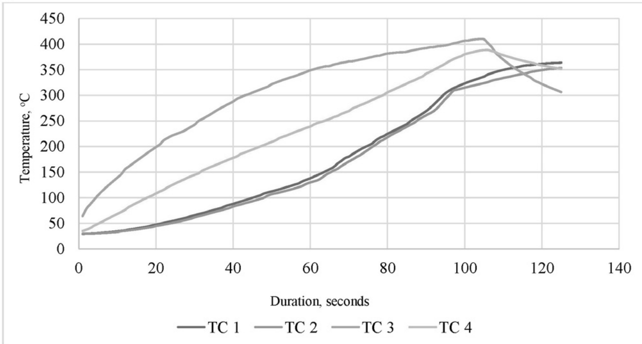

Fig. 4. The results of determining the temperature of the heating of a full-fledged Panasonic NCR18650B power cell from an external source (flame): TC 1, TC 2, thermocouples in the middle of the LIB; TC 3, TC 4, thermocouples on the surface of LIB.

of the power cell and was 20 °C, the initial condition can be written as:

$$t(r,0) = t_0 = 20\ ^{o}\mathrm{C} \quad (2)$$

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

Considering that the heating took place with the help of two burners through an additional metal case, which ensured uniform heating of the surface of the power element case, it is assumed that the heat exchange between the environment and the surface of the LIB case occurs according to the Newton-Richmann's Law of Heat Transfer, which is described by equation (3). It was experimentally established that the law of temperature change of the near-surface (Fig. 5) layer can be displayed in the form of a polynomial function of the 2^{nd}-degree $t = 0{,}0009\tau^2 + 0{,}089\tau + 27{,}993$.

Considering the above, the boundary condition can be written in the form of:

$$-\lambda \frac{\partial t}{\partial r}(r_n,\tau) = \alpha(t(r_n,\tau) - (0{,}0009\tau^2 + 0{,}089\tau + 27{,}993)) \quad (3)$$

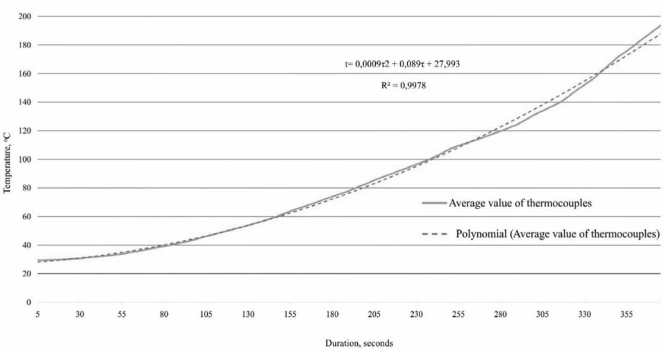

Fig. 5. Results of approximating the temperature change process of the near-surface layer of a full-fledged Panasonic NCR18650B power cell.

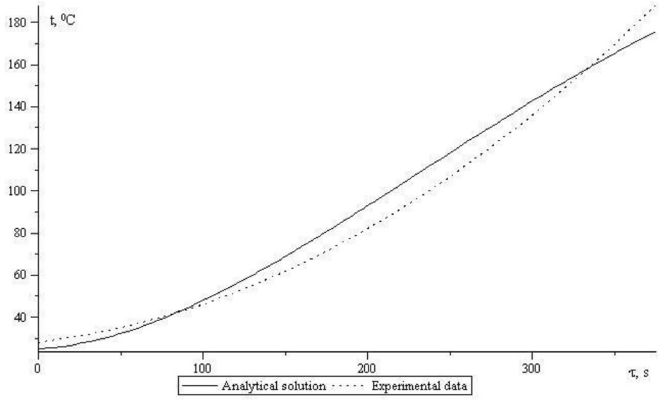

Fig. 6. Comparative results of temperature heating of a full-fledged Panasonic NCR18650B power cell from an external source (flame) and by mathematical modelling method.

Considering that the LIB is a solid body, the symmetry condition must be added to condition (3)

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

The analytical solution to the given problem can be found in detail in (Tatsii *et al.,* 2018; 2020). Analytical mathematical modelling of the heat-transfer process was carried out for a two-layer cylindrical structure, the first layer of which was the filling of a Panasonic NCR18650B power cell, and the second — a metal case.

The following parameters were determined. The generalised thermophysical properties of the filling of the LIB Panasonic NCR18650B were: radius m. (geometric parameters of the power element), specific heat capacity of the material c_0 = 677 J/(kg·K), material density ρ_0 = 4743 kg/m^3 ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ + separator), thermal conductivity of the material λ_0 = 324,9 W/(m·K), which were obtained as results of experiments and mathematical calculations (Lazarenko *et al.,* 2022).

Parameters of the LIB case (steel according to the standards AISI 321) were: radius r_1 = 0,009 m., specific heat capacity of the material c_1 = 470 J/(kg·K), material density ρ_1 = 7800 kg/m^3, thermal conductivity of the material λ_1 = 56 W/(m·K), and coefficient of heat exchange between the surface of the power element and the surface layer α = 55 W/(m^2·K).

The results of mathematical calculations of the process of heating the Panasonic NCR18650B power cell from an external source (flame) are presented in the form of a graph (Fig. 6).

Considering the presented graphical dependence (Fig. 6), it can be seen that the results obtained by mathematical modelling methods are well correlated with the experimental results and can become the basis for further research.

DISCUSSION

Taking into account the various options for the introduction and occurrence of a thermochemical reaction in the LIB, the option of external heating of the LIB can be considered as a last resort. Still, the probability of such a case is quite significant. The emergence of an external high-temperature source (flame) can lead to the heating of the LIB and, as a result, intense ignition of the entire car, and possibly a larger fire.

Experimental results of heating a LIB (fully discharged) with an external high-temperature source (flame) showed the relative safety of such an element, since the combustion of the element itself did not occur even at temperatures above 350 °C. The corresponding result is a testimony and another confirmation that it is the degree of charge of LIB that is the main indicator of its danger. At the same time, the obtained experimental values made it possible to further determine the thermophysical parameters of the LIB, in particular, its internal filling.

The solution of the differential equation of thermal conductivity in the cylindrical coordinate system and the use of the Newton-Richmann Law of Heat Exchange made it possible to carry out mathematical modelling of the heating process of LIB. Further comparison of the experimental values with the mathematical model confirmed the correctness of the experiment, which in the future will make it possible to use the obtained mathematical model in other studies;

Considering the graphical dependence presented (Fig. 6), it can be seen that the results obtained by mathematical modelling methods are well correlated with the experimental results and can become the basis for further research. It should be noted that the largest deviation of the results on temperature was observed at 200 seconds — 81.79 °C for experimental studies and 92.93 for the results of mathematical modelling. This is explained by the not-entirely perfect approximation of the results of experimental research and the accuracy of calculations during mathematical modelling. However, this error is within acceptable values for engineering studies, namely 12–14 %.

The obtained mathematical model based on experimental values made it possible to obtain and confirm thermophysical characteristics of Panasonic NCR18650B ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$).

CONCLUSION

The purpose and objectives of the research, experimental and analytical studies made it possible to establish the following:

– under the condition of the action of an external source of high temperature (flame) and uniform heating of the outer walls of the LIB, its inner part is heated to an average temperature of 168 °C for 70 seconds without further ignition;

– the solution of the differential equation of thermal conductivity in the cylindrical coordinate system and the use of the Newton-Richmann Law of Heat Exchange made it possible to carry out further mathematical modelling of the heating process of similar LIB in the future;

– the obtained mathematical model based on experimental values made it possible to obtain heat exchange between the surface and the subsurface layer (α = 55 W/m^2·K) LIB Panasonic NCR18650B and confirm the corresponding numerical values of specific heat capacity (c_0 = 677 J/kg·K), material density (ρ_0 = 4743 kg/m^3), and thermal conductivity coefficient (λ_0 = 324,7 W/m·K).

REFERENCES

Domarch, C., Cherchi, E. (2023). Electric vehicle forecasts: a review of models and methods including diffusion and substitution effects. *Transport Rev*., **43** (6), 1118–1143. https://doi.org/10.1080/01441647.2023.2195687.

Dong, Y., Meng, J., Sun, X., Zhao, P., Sun, P., Zheng, B. (2023). Experimental study on effects of triggering modes on thermal runaway characteristics of lithium-ion battery. *World Electr. Veh. J*., **14** (10), 270. https://doi.org/10.3390/wevj14100270.

EV fires — current data (2023). https://www.evfiresafe.com/ev-battery-fire-data.

Golubkov, W., Fuchs, D., Wagner, J., Wiltsche, H., Stangl, C., Fauler, G., Voitic, G., Thaler, A., Hacker, V. (2014). Thermal-runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes. *RSC Adv*., **4**, 3633. https://doi.org/10.1039/C3RA45748F.

Hoelle, S., Scharner, S., Asanin, S., Hinrichsen, O. (2021). Analysis on thermal runaway behavior of prismatic lithium-ion batteries with autoclave calorimetry. *J. Electrochem. Soc*., **168**, 120515. https://doi.org/10.1149/1945-7111/ac3c27.

Kozma, J., Benkara, K. E. K., Dib, R., Forgez, C., Moubayed, N. (2023). Aging determination of lithium ion batteries based on thermal measurements. *IEEE Vehicle Power and Propulsion Conference, Milan, Italy 24–27 October*. Milan, p. 6. https://doi.org/10.1109/VPPC60535.2023.10403235.

Lazarenko, O., Berezhanskyi, T., Pospolitak, V., Pazen, O. (2022). Experimental evaluation of the influence of excessive electric current on the fire hazard of lithium-ion power cell. *Eastern-Eur. J. Enterprise Technol*., **4** (10), 67–75. https://doi.org/10.15587/1729-4061.2022.263001.

Lazarenko, O., Berezhanskyi, T., Pospolitak, V., Pazen, O. (2023). Assessing the effect of mechanical deformation of the Panasonic NCR18650B lithium-ion power cell housing on its fire safety. *Eastern-Eur. J. Enterprise Technol*., **2** (7), 69–78. https://doi.org/10.15587/1729-4061.2023.276780.

Lazarenko, O. V., Pazen, O. Yu., Sukach, R. Yu., Pospolitak, V. I. (2022). Experimental evaluation of fire hazard of lithium-ion battery during its mechanical damage. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, № 5, pp. 68-73. https://doi.org/10.33271/nvngu/2022-5/068.

Lee, C., Said, A. O., Stoliarov, S. I. (2020). Passive mitigation of thermal runaway propagation in dense 18650 lithium ion cell assemblies. *J. Electrochem. Soc*., **167**, 090524. https://doi.org/10.1149/1945-7111/ab8978.

Li, K., Wu, Y., Wang, J., Wang, S. (2017). Experimental study on thermal characteristics and temperature distribution of laminated lithium-ion power battery. *Energy Proc*., **142,** 3338–3343. https://doi.org/10.1016/j.egypro.2017.12.467.

Liang, K., Zhu, Q., Zhou, X. (2023). Simulation and characteristic analysis of high-temperature thermal runaway process in ternary lithium-ion batteries. *Research Gate*, 17. https://doi.org/10.21203/rs.3.rs-3459779/v1.

Liu, Y., Niu, H., Li, Z., Liu, J., Xu, C., Huang, X. (2021). Thermal runaway characteristics and failure criticality of massive ternary Li-ion battery piles in low-pressure storage and transport. *Proc. Safety Environ. Protect*., **155**, 486–497. https://doi.org/10.1016/j.psep.2021.09.031.

Parkhomenko, V.-P., Lazarenko, O., Sukach, R. (2023). Analysis of equipment for extinguishing electric vehicles and development of recommendations for their extinguishing. *Fire Safety*, **42**, 74–84. https://doi.org/https://doi.org/10.32447/20786662.42.2023.09.

Ruiza, V., Pfranga, A., Kristona, A., Omarb, N., Bosscheb, P. van den, Boon-Bretta, L. (2018). A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles. *Renew. Sust. Energy Rev*., **81**, 1427–1452. https://doi.org/10.1016/j.rser.2017.05.195.

Sun, P., Bisschop, R., Niu, H., Huang, X. (2020). A review of battery fires in electric vehicles. *Fire Technol*., **56**, 1361–1410. https://doi.org/10.1007/s10694-019-00944-3.

Tan, Y., Li, Y., Gu, Y., Liu, W., Fang, J., Pan, C. (2024). Numerical study on heat generation characteristics of charge and discharge cycle of the lithium-ion. *Battery Energies*, **17** (1), 178. https://doi.org/10.3390/en17010178.

Tatsii, R. M., Pazen, O. Y. (2018). Direct (classical) method of calculation of the temperature field in a hollow multilayer cylinder. *J. Eng. Phys. Thermoph*., **91**, 1373–1384. https://doi.org/10.1007/s10891-018-1871-3.

Tatsii, R. M., Pazen, O. Y., Shypot, L. S. (2020). Research of the temperature field in the system of multilayer cylindrical solid bodies under fire conditions. *Fire Safety*, **37**, 64–71. https://doi.org/10.32447/20786662.37.2020.10.

Weber, N., Schuhmann, S., Tübke, J., Nirschl, H. (2023). Chemical thermal runaway modeling of lithium-ion batteries for prediction of heat and gas generation. *Energy Technol*., **11** (10), 2300565, 12. https://doi.org/10.1002/ente.202300565.

Xie, J., Xie, N., Liu, Y. (2018). Analysis of the thermal characteristics and thermal management of lithium-ion power battery. *Adv. Eng. Res*., **162**, 427–433. https://doi.org/10.2991/icammce-18.2018.94.

Yu, Y., Zhang, J., Zhu, M., Zhao, L., Chen, Y., Chen, M. (2023). Experimental investigation on the thermal management for lithium-ion batteries based on the novel flame retardant composite phase change materials. *Batteries*, **9**, 378. https://doi.org/10.3390/batteries9070378.

Zhang, M., Xu, H., Ma, N., Pan, X. (2022). Intelligent vehicle sales prediction based on online public opinion and online search index. *Sustainability*, **14** (16), 10344. https://doi.org/10.3390/su141610344.

Received 12 May 2024
Accepted in the final form 24 September 2024

PANASONIC NCR18650B LITIJA JONU BATERIJAS TERMISKO UN FIZIKĀLO PARAMETRU NOTEIKŠANA

Uz eksperimentālu datu pamata izstrādāts matemātisks modelis, lai noteiktu Panasonic NCR18650B litija jonu baterijas termiskos un fizikālos parametrus paaugstinātas ārējās temperatūras gadījumā.