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This study explores a process underlying the onset and evolution of an irreversible thermochemical reaction that fills a lithium-ion battery (LIB) internally. The issue related to early detection of the onset of thermal decomposition of LIB internal filling is that today there are no unified approaches and clearly defined parameters that would make it possible to predict the failure of LIB. The process of LIB thermal decomposition can occur without visual signs and rapidly develop into intense combustion. Obtaining parameters for the onset of the evolution of LIB's internal filling thermochemical reaction provides prerequisites for designing a sensor for early detection of LIB thermal decomposition.

Based on the results from analytical processing of existing experimental studies on determining the chemical composition of the products of LIB thermal decomposition, the basic parameters have been established. In particular, the change in the concentration of CO₂, HF, and P_{abs} was found to be the basis for further advancement of the model (mathematical basis) of the fuzzy correction unit.

A fuzzy correction module using the Mamdani algorithm has been designed for a multi-channel sensor for early detection of thermal decomposition (SEDTD) in LIB. The forms and parameters of the input and output membership functions have been established. A database of fuzzy rules has been compiled that describe LIB's possible states. Simulation in the Fuzzy Logic Toolbox package in the MATLAB environment (USA) qualitatively reflects the perception of input signals about the onset and evolution of a thermochemical reaction.

The results of simulation studies have confirmed the effectiveness of the proposed approach. It has been established that the sensor, based on a comprehensive analysis of input parameters such as pressure, CO₂ and HF concentrations, forms an information output signal that adequately reflects the technical condition of LIB, in particular normal, pre-fire (pre-emergency), and fire (emergency) states

Keywords: lithium-ion battery, sensor, combustion, thermal decomposition, triggering algorithm, Fuzzy Logic

DESIGN OF AN INTELLIGENT MULTI-CHANNEL SENSOR FOR EARLY DETECTION OF THERMAL DECOMPOSITION IN A LITHIUM-ION BATTERY

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1. Introduction

Alternative energy sources are becoming increasingly popular and widespread in various domains of human activity. The use of solar panels, wind turbines has always been perceived as a centralized alternative energy source for small settlements inaccessible to the average person. Today, for example, a solar panel is a means of individual use and generation of energy for a small lighting device, light bulb, video surveillance camera, etc. available to the general public. Modern achievements of science and technology have become available for use by humans from the smallest household appliances to large and powerful systems for accumulat-

ing and generating electricity for both individual households and powerful commercial state-owned enterprises.

In most cases, high-power battery packs based on lithium-ion batteries (LIBs) are used to accumulate electricity. At the same time, LIB is an integral component of modern electric cars, scooters, bicycles. However, practical experience in the use of LIBs [1] and scientific research shows their significant fire hazard [2], leading to large-scale fires and material losses [3]. The results of comprehensive studies on the specifics and causes of LIB combustion indicate a rapid increase in temperature indicators and flaming combustion of LIBs during the onset of processes associated with the thermochemical decomposition of the internal filling of the element.

Thus, the use of conventional fire detectors or means of recording the onset of combustion will be ineffective since they will record the already accomplished fact of the development of LIB combustion or a rechargeable battery (RB).

Accordingly, laying a scientifically sound basis for establishing indicators that precede the onset of the rapid development of the thermochemical decomposition of the internal filling of LIB is an urgent issue, which is the basis for further scientific research. At the same time, the establishment of individual indicators that will precede the evolution of combustion of LIB provides grounds for developing an algorithm for the operation of a fundamentally new sensor for detecting the onset of thermal decomposition of LIB or RB. Additionally, the results could serve for further systemic application in battery storage and electricity storage systems in order to prevent the development of combustion and to activate stationary or local fire extinguishing systems.

2. Literature review and problem statement

In work [4], based on COMSOL Multiphysics, taking into account the regularities of thermochemical decomposition of LIB, an algorithmic model of thermal decomposition and increase in temperature indicators of LIB was built, in particular in the battery packs of electric vehicles. Experimental studies using the proposed model showed that the rate of temperature increase can significantly characterize the onset of a thermochemical reaction, and when the rate of temperature increase exceeds 1°C/s , LIB has a high probability of ignition. The results provided grounds for further research; however, the work did not highlight direct ideas and ways of further implementation.

In study [5], an analysis of existing gas-sensitive elements was conducted, which can determine the onset of LIB's thermochemical reaction evolution. Based on the results, it was found that electrolyte vapors in the form of CO, CO₂, and CH₄ can be effective markers of the onset of LIB combustion. Further analysis of existing technologies and means of detecting the relevant gases revealed that individual gas analyzers do exist; however, the issue of the availability of a multi-gas analyzer for CO, CO₂, and CH₄, especially for LIB, requires further study and development. Accordingly, there is no ready-made solution today. Thus, based on the results reported in [5], a roadmap has been devised that defines the rational design of next-generation gas-analyzing materials and accelerates the implementation of gas-sensitive element technology to improve LIB safety. The objective reason for the complexity of designing relevant gas analyzers is the difficulties associated with the technical side of fabricating such devices, especially their adjustment to low concentrations of substances in the environment.

A number of studies have been devoted to solving scientific problems related to the investigation of methods and means for the early detection of the onset of thermal decomposition in battery energy storage systems, in particular [6, 7]. In [6], the main current approaches to the possibility of determining the onset of LIB combustion are determined. In particular, it was established that promising methods include acoustic, gas analytical, electrical (changing the parameters of element consumption), and optical. In addition, in work [7], the results of research on the possibility of monitoring the onset of combustion using the parameters of pressure increase and changes in the electrical performance of elements are reported. The proposed approach to assessing the electrical performance of LIB could prove effective if there is a small number of elements.

However, if there are thousands of LIBs, other solutions are required. An option for overcoming the relevant difficulties may be the development of monitoring software based on artificial intelligence or other digital solutions.

In particular, in [8], researchers devised a method for ultrasonic determination of critical LIB parameters for the purpose of monitoring the onset of combustion of batch LIBs. The effectiveness of the proposed method was additionally verified experimentally, which confirmed its effectiveness in early detection of LIB combustion. The complexity of the resulting method is the need to determine the individual parameters for each LIB in the battery assembly. Thus, the proposed method requires further improvement and investigation.

The increase in the LIB's temperature indicators during operation is a key indicator of the onset of the thermochemical reaction of the element. Work [9] reports the results of designing a wireless sensor for monitoring the temperature indicators of the LIB format 21700. At the same time, the work determines that the indicators of monitoring the gas environment and the integrity of the element can also be monitored using wireless communication technology. However, despite the declared ideas, the work does not describe ready-made technical solutions or methods for solving the tasks set.

The most reliable and accurate indicator of changes in the parameters of LIB operation is the change in the electrical parameters of the element, in particular its internal resistance. Thus, in study [10], the dependence of the spectrum of the electrochemical resistance of LIB on changes in temperature and deformation of the element was established. The proposed method uses a two-stage warning method with three indicators in three frequency ranges. In accordance with the proposed methodology, a number of complex experimental studies were conducted on batch and cylindrical LIBs, which confirmed the effectiveness of the proposed approach. Since all studies were conducted under laboratory conditions, the question of the effectiveness and practicality of the proposed method under real conditions remains undetermined as large and expensive laboratory equipment is used for the study.

A comprehensive method for analyzing and assessing the probability of LIB ignition is given in [11]. The researchers developed a comprehensive algorithm for assessing the indicators and risk of irreversible thermochemical reaction of LIB. Thus, electrochemical indicators were taken into account: voltage, gas concentration (CO, H₂) and temperature indicators. So, a three-stage model for assessing the risk of ignition of LIB was obtained. The research findings contain theoretical results confirmed experimentally, but not tested under real conditions, and their actual practical application has not been determined. The reason may be objective difficulties associated with the complexity of manufacturing the corresponding full-scale samples and the general funding of research.

Analysis and combination of a number of parameters for designing a multi-sensor for detecting early thermal decomposition of LIB is becoming an urgent task. Thus, in [12], the mechanism of fire occurrence and the causes of its occurrence were analyzed, the calculation method and the main conditions for assessing the parameters of the onset of thermal decomposition of LIB were determined, and then a combustion propagation model was built. Additionally, a model of fire detection and early warning of combustion was proposed, on the basis of which experimental studies were conducted. The results demonstrated the possibility of detecting a probable ignition of LIB 10–15 minutes before the start of the thermochemical reaction. Despite the reasonable

indicators of the proposed model, the issue of the immediate start of combustion was not covered in [12]. The parameters of LIB operation taken in the work are close to the conditions of standard operation and do not take into account the rate of increase in hazard indicators under the condition of non-standard operation of LIB.

The electrical parameters of LIBs are key indicators during their operation and are directly monitored and tracked using various control tools, for example, Battery Management System (BMS) boards. Research and development of algorithms for system monitoring of LIB voltage, in particular for electric vehicles, is a relevant scientific issue.

Thus, in work [13], a method for early warning of failure and probable ignition of LIB based on GRU-LSTM for classifying voltage faults was investigated. The authors propose a new hybrid neural network with a logical recurrent unit and long short-term memory (GRU-LSTM) for predicting the voltage of LIB of an electric vehicle. The feasibility of the proposed method is verified by developing hierarchical warning rules based on forecasting data to implement accurate warning of multiple voltage anomalies. The proposed approach is a modern stage of development of monitoring the state of LIB but requires testing under real conditions, and in particular, taking into account the possibility of preventing LIB fires. The absence of full-scale experimental testing and corresponding empirical data is evident, since such studies require additional funding and consequently increase the overall research costs.

Papers [14, 15] are considered fundamental in the study of the features of thermal decomposition of the internal filling of LIBs. Studies [14, 15] show that regardless of the type of chemical composition of the anode and cathode, initially, as a result of the increase in the internal temperature of the element, melting (thermal decomposition) of the solid electrolyte occurs inside the element at a temperature of 70–120°C. Considering that the studies were carried out at the initial stages of LIB development, without taking into account the variable chemical filling of LIB, the results do not provide a complete characteristic and description of the features of the thermochemical reaction.

Study [16] supplements the existing knowledge regarding the features of the thermal decomposition in LIB. Thus, in work [16] it is noted that the further course of thermal decomposition is accompanied by a violation of the contact of the interface of the surfaces of the solid electrolyte with the anode of the element, which leads to the release of a group of combustible gases CH. Also, thermal decomposition products of the solid electrolyte are formed, which form such compounds as DMC (dimethyl carbonate), PC (propylene carbonate), EC (ethylene carbonate).

The results reported in [17, 18] indicate that a further increase in the temperature indicators of LIB leads to a reaction and interaction directly between the cathode and the anode of the element (as a result of the complete destruction of the separating layer 135–166°C), which leads to a short circuit and more intense gas and heat release, and subsequent combustion. The chemical composition of the thermal decomposition products will depend on the type of cathode used in the LIB. Accordingly, the decomposition will produce metal oxides, such as Co_3O_4 for LCO (lithium cobalt oxide) cells [17], $\text{Li}_x\text{Co}_y\text{Al}_z\text{O}_p$ for NCA, (Mn, Ni)O and $\text{Li}_x(\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3})\text{O}_2$ for NCM (nickel cobalt manganese) cells [18].

A significant body of research [19–21] describe in detail the thermal decomposition and combustion, in particu-

lar of such substances as DMC, PC, EC. In study [19], it is noted that as a result of an increase in temperature to about 300°C, DMC undergoes rapid decomposition into such substances as methanol (CH_3OH), methane (CH_4), dimethyl ether (CH_3OCH_3), acetic acid (CH_3COOH), in addition to already existing and present compounds such as carbon monoxide, carbon dioxide. In [20, 21], a description of the thermal decomposition of the starting compounds DMC and EMC (ethyl methyl carbonate, $\text{C}_4\text{H}_8\text{O}_3$) at a temperature of 180–300°C is given. It is determined that DMC is obtained as a result of the primary decomposition of EMC as a result of an exchange reaction. Papers [19–21] report more analytical and theoretical research results that do not provide a clear definition and establishment of the concentration distribution of chemicals in the air during thermal decomposition of LIB.

Among the significant number of scientific results on determining the features of thermal decomposition of the internal filling of LIB, it is worth considering the results of experimental studies from [22]. The work reports informative results from the point of view of the distribution of the concentration of combustion products depending on the temperature indicators of the cylindrical LIB NCA (lithium-nickel-cobalt-aluminum oxide) format 18650. The work uses modern methods of analysis of indicators, in particular the spectrographic method of analysis of combustion products (FT-IR Spectrum 3, Perkin Elmer). The experimental setup allowed the authors to obtain results under the condition of variable LIB heating parameters from 5–10°C/min both under inert gas (N_2) and under normal environmental conditions. In addition, based on the results of the study, the parameters of change in ambient pressure due to the burning of LIB were established.

Taking into account our review of the literature [4–22], it can be stated that most studies define general ways and approaches to solving the issues of early detection of the possibility of a LIB ignition. The unifying factor of papers [6, 7] is the establishment of such indicators as the presence of (specific) combustion products, changes in voltage and resistance of the element as the determining and most reliable indicators preceding the burning of LIB. Theoretical and experimental studies on the development of algorithms and sensors for detecting the burning of LIB focus on taking into account at least three critical indicators of the element. This approach allows for a phased distribution of factors preceding the occurrence of a thermochemical reaction in accordance with the stages of the evolution of LIB combustion. Thus, the distribution of general and critical indicators of the probability of LIB ignition is carried out. The results show that the practical dominance of the obtained analysis algorithms or approaches requires experimental confirmation under real conditions with subsequent refinement and implementation.

Our review of available research results on determining combustion products and thermal decomposition of LIB as a result of an irreversible thermochemical reaction, regardless of the type of LIB and its chemical composition, according to [4–22], is summarized in Table 1.

The results in Table 1 give a variable number of compounds and chemicals formed as a result of the thermochemical reaction. Among the variety of compounds and substances, it can be noted that such substances as CO_2 , DMC, EMC, HF emerge throughout the entire thermal decomposition of the chemical filling of LIB. However, DMC, EMC, according to the results of the research, are unstable compounds and during combustion and an increase in temperature indicators

can decompose into secondary compounds, such as CH₃OH, CH₃OC₂H₅, etc.

4. The study materials and methods

Table 1
Summary table of chemical substances and compounds formed during thermal decomposition of the internal filling of LIB according to research review

LIB temperature, °C	Thermochemical reaction	Thermal decomposition products			DMC	EMC	
300		H ₂	HF	DMC	CH ₃ OH	C ₂ H ₅ OC ₂ H ₅	
		EMC			CH ₃ OC ₂ H ₅		
200–240		CO	CO ₂	CH ₃ F	CH ₃ OH		
				DMC			EMC
170–180		O ₂	HF	PF ₅	C ₂ H ₄	CH ₃ OC(=O)H	
			CO ₂	DMC	EMC	CH ₃ OCH ₃	
120–140	C ₃ H ₆	C ₂ H ₄	CH ₄	No decomposition			
70–90	C ₂ H ₄	CO ₂	O ₂				

In papers [4–13], there is no single proven approach, definition of an algorithm, technical means of early detection of thermal decomposition of LIB. The results of studies [14–22] determine only the features of thermal decomposition and describe in detail the process and products of thermal decomposition that are released. However, they do not determine the purpose of the study to determine the main parameters that are of particular importance when designing appropriate devices or sensors to detect the onset of LIB thermal decomposition. The reviewed literature [4–22] in most cases focuses on determining the critical parameters of the thermal decomposition indicators of LIB and the corresponding algorithms for their determination, rather than the algorithmic development of the LIB early thermal decomposition sensor (SEDTD).

Accordingly, there is a need to conduct further research into this area. In particular, to devise an alternative method for determining the onset of thermal decomposition of LIB. None of the above studies has established a single experimentally and practically confirmed technique or approach for early detection of the onset of thermal decomposition of LIB. Specifically, the issue of a direct technical means that could carry out appropriate monitoring of the relevant indicators remains unresolved.

The above gives grounds to argue that it is advisable to conduct research on the design of an intelligent multi-channel SEDTD for LIB taking into account the indicators of an increase in the concentration of thermal decomposition products in LIB.

3. The aim and objectives of the study

The purpose of our study is to design a sensor for early detection of the onset of thermal decomposition of LIB based on a fuzzy logic model taking into account the indicators of LIB thermal decomposition.

To achieve the goal, the following tasks were set:

- to establish relevant parameters and characteristics that will define the onset and evolution of thermal decomposition of LIB's internal filling;

- to design a model of a fuzzy correction module for the sensor for early detection of fire in LIB taking into account the form and parameters of the input and output membership functions, the number of linguistic terms, and to construct a base of fuzzy rules;

- to build a model of SEDTD for LIB based on the fuzzy logic module and to investigate its operation.

The object of our study is the process of initiation and evolution of an irreversible thermochemical reaction in the internal filling of a lithium-ion battery.

The principal hypothesis of the study assumes that during the onset of thermal decomposition of the internal filling of LIB, thermal decomposition products of various chemical compositions are released and the parameters of the surrounding environment change. According to the research hypothesis, there is an opportunity to design technical means that would provide the possibility of early detection and prevention of the occurrence of thermal decomposition of the internal filling of LIB, taking into account the individual characteristics of LIB.

According to the research hypothesis, the course of thermal decomposition of the internal filling of LIB, and especially the initial thermochemical processes of the decomposition of a LIB cathode, will occur with the release of specific substances and compounds. The detection of such substances will be evidence of the beginning of thermochemical decomposition of LIB. This approach, combined with additional parameters of LIB combustion, will make it possible to detect LIB combustion at early stages.

The assumptions adopted in the study are that the designed model of SEDTD for LIB on the basis of the fuzzy logic module could enable the implementation of this sensor on a microprocessor with results adequate to the modeling within acceptable limits.

In order to optimize the thermal decomposition indicators of LIB during the construction of the fuzzy correction module model, only the thermal decomposition products of LIB were taken into account, which are present in significant concentrations and on a permanent basis.

To obtain key and unifying indicators preceding the onset of thermal decomposition of the internal filling of LIB, an analytical method of analyzing existing results of experimental studies on determining the chemical composition of thermal decomposition products of LIB was used. The application of existing research results is justified since they were carried out using the most modern equipment and advanced technologies. Also, the obtained indicators will be compared in the future in order to determine the most repeatable research results.

In order to build a model (mathematical basis) of the fuzzy correction module and SEDTD, the Fuzzy Logic Toolbox and Simulink packages in the MATLAB environment were used. The software is a specialized set of functions for analysis, design, and modeling of systems constructed on the basis of fuzzy set theory. For direct calculation of the model, Mamdani's fuzzy inference method was used, whereby the output function is a fuzzy variable for each rule. The use of this approach makes it possible to carry out hardware implementation of the fuzzy module based on existing and available processors.

Fuzzy logic makes it possible to work with imprecise, fuzzy, and linguistically described data. Unlike classical systems in which a variable can only take the values 0 or 1, in fuzzy logic the degree of membership of an element to the set is determined by a real number from the interval [0,1] $\mu_A(x) \in [0, 1]$, where $\mu_A(x)$ is a membership function that determines the degree of correspondence of value x to the fuzzy set A .

The synthesis of the fuzzy correction module is carried out according to the methodology from [23, 24], using the classical Mamdani fuzzy inference algorithm. This algorithm is one of the most common in technical diagnostics and control problems due to its intuitive clarity and the ability to interpret expert knowledge in the form of linguistic rules.

Formally, the knowledge base of the fuzzy inference system is given as a set of rules of the type:

$$\text{If } x_{1k} \in A_{1k} \text{ and } x_{2k} \in A_{2k} \text{ and } \dots \text{ and } x_{nk} \in A_{nk}, \text{ then } Y \in C_k, \tag{1}$$

where $x_{1k}, x_{2k}, \dots, x_{nk}$ – values of input parameters characterizing the state of the system;

$A_{1k}, A_{2k}, \dots, A_{nk}$ – fuzzy sets (linguistic terms) that describe the permissible ranges of change of input signals;

C_k – fuzzy set of the output variable Y , corresponding to a certain state of the object.

This approach makes it possible to adequately describe real physical processes that are inherently uncertain or difficult to formalize with accurate mathematical models, which is appropriate for the achieved goal of the work.

5. Results of designing a sensor for early detection of thermal decomposition of lithium-ion battery's internal filling

5.1. Determining the necessary parameters for the thermal decomposition of lithium-ion battery

Taking into account chemical composition and structure of LIB, the onset of evolution and course of irreversible thermochemical reaction can be divided into the following stages: decomposition of solid electrolyte, reaction of lithium elements with electrolyte, destruction of separating layer (separator). Additionally, reaction of binding and basic chemical substances and compounds occurs.

Using published results [22], an analysis of initial compounds and substances was carried out. In particular, it was established that the concentration of CO and CO₂ is present during thermal decomposition and subsequent combustion of LIB in the highest concentrations. Since the concentration of CO₂ is a more stable compound, we shall take it for analysis of early detection of the stage of beginning of thermal reaction in LIB. After processing experimental data [22], the total change in CO₂ concentration is shown in Fig. 1, which allowed us to derive a third-order polynomial

dependence of the change in the concentration of the corresponding substance.

Given the obtained characteristic (Fig. 1), it is possible to establish the dependence of the distribution of CO₂ concentration during the thermal decomposition of LIB, which is described by the following equation

$$y = 19.964x^3 - 821.32x^2 + 8421.2x + 834.62. \tag{2}$$

The coefficient of reproducibility in equation (2) is $R^2 = 0.9792$, which is a significant factor in the accuracy of the derived equation.

Based on the results of our analysis of the data, the presence of the chemical compound HF was confirmed, the concentration of which was absent, although not significant. But it changed steadily during study [22]. Obtaining such results makes it possible to take into account the presence of such a compound as a special individual indicator of thermal decomposition of LIB, which allows us to identify the development of the thermochemical reaction. The graphical dependence of change in the concentration of HF is shown in Fig. 2.

Given the obtained characteristic (Fig. 2), it is possible to establish the dependence of the HF concentration distribution during the thermal decomposition of LIB, which is described by the following equation

$$y = 0.1862x^3 - 6.7932x^2 + 65.554x - 2.5321. \tag{3}$$

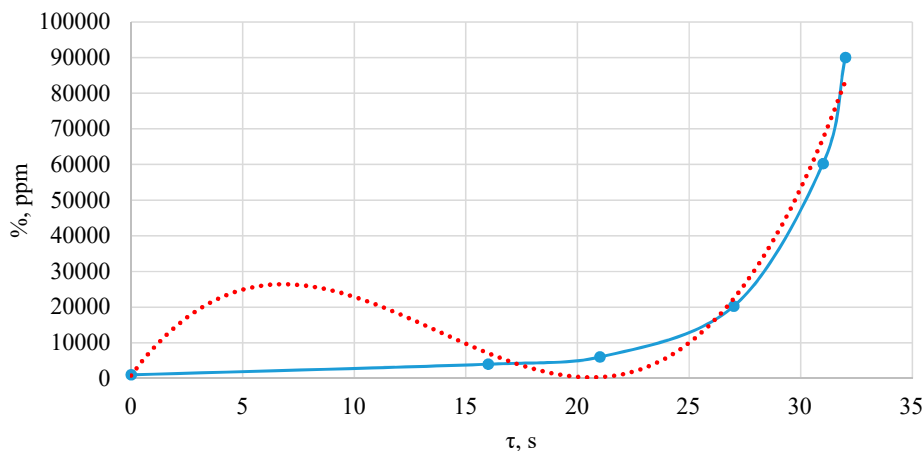


Fig. 1. Graphical dependence of change in CO₂ concentration during thermal decomposition of the lithium-ion battery NCA 18650 with a third-order polynomial trend line in accordance with experimental studies [22]

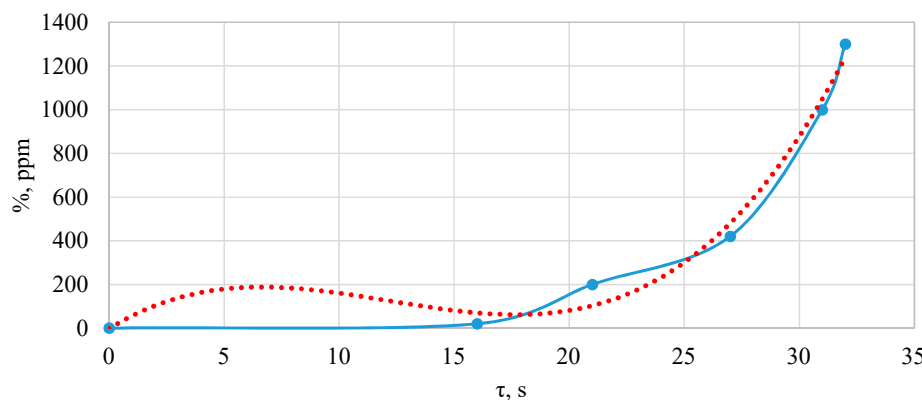


Fig. 2. Graphical dependence of the change in HF concentration during thermal decomposition of the lithium-ion battery NCA 18650 with a third-order polynomial trend line in accordance with experimental studies [22]

The reproducibility coefficient in equation (3) is $R^2 = 0.9853$, which is a significant factor in the accuracy of the derived equation.

An additional parameter worth paying attention to during the study and in general during the thermal decomposition and subsequent combustion of LIB is the change in pressure (Fig. 3).

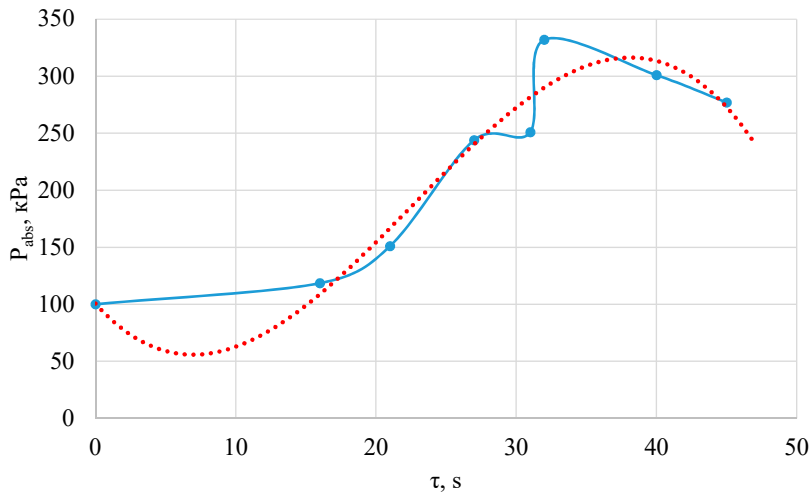


Fig. 3. Graphical dependence of pressure change during thermal decomposition of the lithium-ion battery NCA 18650 with a third-order polynomial trend line in accordance with experimental studies [22]

Given the obtained characteristic (Fig. 3), it is possible to establish the dependence of pressure change during the thermal decomposition of LIB, which is described by the following equation:

$$y = -0.0172x^3 + 1.1626x^2 - 13.681x + 100.51, R^2 = 0.9395. (4)$$

The coefficient of reproducibility in equation (4) is $R^2 = 0.9395$, which is smaller than the previous ones, but still significant.

Taking into account the intensive gas release, the increase in pressure indicators is the most sensitive in terms of the speed of registration of the corresponding parameter.

In order to further process the resulting experimental dependences of change in the concentration of CO₂, HF, and the pressure of the medium, a polynomial trend line of the third order was superimposed on the graphical dependences and equations were derived that describe the dependences depicted in Fig. 1–3 with an error within 7–3%. The resulting equations make it possible to further construct the fuzzy logic module model of SEDTD for LIB.

5. 2. Building a model of the fuzzy correction unit for the thermal decomposition sensor in a lithium-ion battery

The input values of the fuzzy correction unit are three parameters that characterize the current state of LIB: pressure, CO₂ concentration, HF concentration. Each of these input variables will have three linguistic terms.

For the first input variable “Pressure”: HP (High) – high value; EP (Elevated) – elevated value; NP (Normal) – normal value.

For the second input variable “CO₂”: HC (High) – high value; EC (Elevated) – elevated value; NC (Normal) – normal value.

For the third variable “HF”: HHF (High) – high value; EHF (Elevated) – elevated value; NHF (Normal) – normal value.

The output of the module is a signal that reflects a generalized assessment of the system state and is used for decision-making. The output of the module will also have three linguistic terms: Fire – fire; Im50% – probability of fire 50% (pre-fire state); Norm – Normal (norm).

One of the key stages in the synthesis of a fuzzy inference system is the selection of the form and parameters for membership functions. They determine the mapping of clear input values into fuzzy sets. The accuracy, stability, and interpretability of the model largely depend on the correctness of this choice.

For each input variable, a set of linguistic terms is introduced that reflect the qualitative states of the system parameters. Membership functions for extreme terms (such as Normal and High) are given by a trapezoidal form. This makes it possible to highlight saturation regions in which the value of the variable uniquely belongs to the corresponding term. For the intermediate term, a triangular membership function is used, which provides a smooth transition between neighboring states.

Determining the parameters of membership functions for the output variable is a more complex task. This task requires a series of simulation experiments to achieve optimal accuracy. We assume the membership functions of the output variable for the extreme terms (such as Fire and Norm) of a trapezoidal shape. For the intermediate term (Risk of fire), a triangular membership function is used.

This choice is due to a compromise between the accuracy of approximation and computational complexity. Triangular and trapezoidal membership functions are given by piecewise linear dependences, which ensures their computational simplicity and effective implementation in fuzzy inference algorithms, especially in real-time systems. At the same time, they provide sufficient accuracy of the description of fuzzy sets in most engineering applications.

Based on the analysis of the curves of pressure, CO₂, HF, the permissible ranges of change of input and output quantities (Table 2) are determined on the appropriate scale. This allows for correct normalization of signals and increases the accuracy of fuzzy output.

Table 2

Parameters for membership function of the input and output variables

Term	Term shape	Characteristic points
HP (High value)	trapezoid	[6, 8, 10, 12]
EP (Elevated value)	triangle	[3, 5, 7]
NP (Normal value)	trapezoid	[-1, 0, 2, 4]
HC (High value)	trapezoid	[6, 8, 10, 12]
EC (Elevated value)	triangle	[3, 5, 7]
NC (Normal value)	trapezoid	[-1, 0, 2, 4]
HHF (High value)	trapezoid	[6, 8, 10, 12]
EHF (Elevated value)	triangle	[3, 5, 7]
NHF (Normal value)	trapezoid	[-1, 0, 2, 4]
Fire (Fire)	trapezoid	[0.6, 0.8, 1, 1.2]
R50% (Risk of fire)	triangle	[0.3, 0.5, 0.7]
N (Normal)	trapezoid	[-0.1, 0, 0.2, 0.4]

Having three input variables pressure, CO₂, HF, each of which has three linguistic terms, expression (1) can be written as follows

$$\text{If } x_1 \in A_{1k}, x_2 \in A_{2k}, x_3 \in A_{3k}, \text{ then } Y \in C_k, \quad k = 1, \dots, 27. \quad (5)$$

The rule base is formed on the basis of expert knowledge and the results of the analysis of the dynamic characteristics of the input and output variables. After modeling, the rule base can be refined in order to increase the accuracy and reliability of the system. Table 3 gives the rule base. As noted above, the task of the fuzzy correction unit is to reliably detect battery fire, even before the appearance of an open flame, as well as to prevent false triggering from external sources not related to the fire.

Table 3

Fuzzy rule base

No.	Pres-sure	HF	CO ₂	Alarm
1	0	0	0	0
2	0	0	50%	0
3	0	0	100%	50%
4	0	50%	0	50%
5	0	50%	50%	50%
6	0	50%	100%	100%
7	0	100%	0	100%
8	0	100%	50%	100%
9	0	100%	100%	100%
10	50%	0	0	0
11	50%	0	50%	50%
12	50%	0	100%	100%
13	50%	50%	0	50%
14	50%	50%	50%	100%
15	50%	50%	100%	100%
16	50%	100%	0	100%
17	50%	100%	50%	100%
18	50%	100%	100%	100%
19	100%	0	0	50%
20	100%	0	50%	100%
21	100%	0	100%	100%
22	100%	50%	0	100%
23	100%	50%	50%	100%
24	100%	50%	100%	100%
25	100%	100%	0	100%
26	100%	100%	50%	100%
27	100%	100%	100%	100%

The fuzzy correction unit model was developed using the Fuzzy Logic Tool-

box in the MATLAB environment. Fig. 4, 5 show windows of the surface of the output signal formed by the fuzzy correction module at different values of pressure, CO₂, HF. A composite rule base is implemented.

From Fig. 4, 5 it is seen that at a certain value of pressure, CO₂, HF at the output of the fuzzy correction unit the value of the output signal is formed (to which surface plane the signal “Output” belongs), which corresponds to “Norm”, “Probability of fire 50%”, “Fire”. A pre-compiled rule base is implemented.

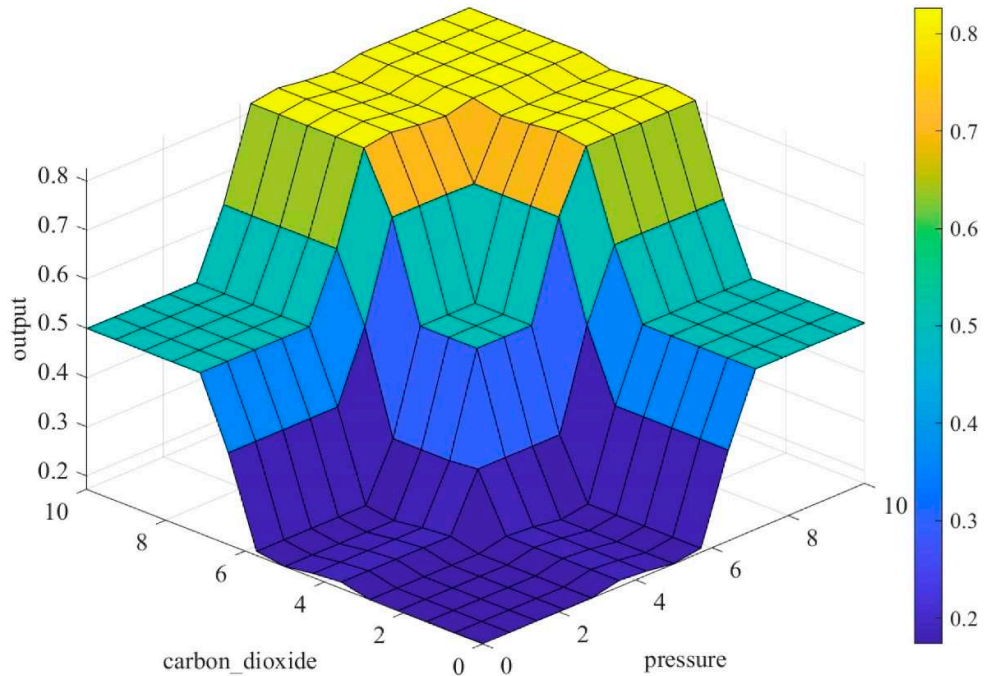


Fig. 4. Window surface of the output signal formed by the fuzzy correction module, when the pressure and CO₂ change, the output signal HF is unchanged 3

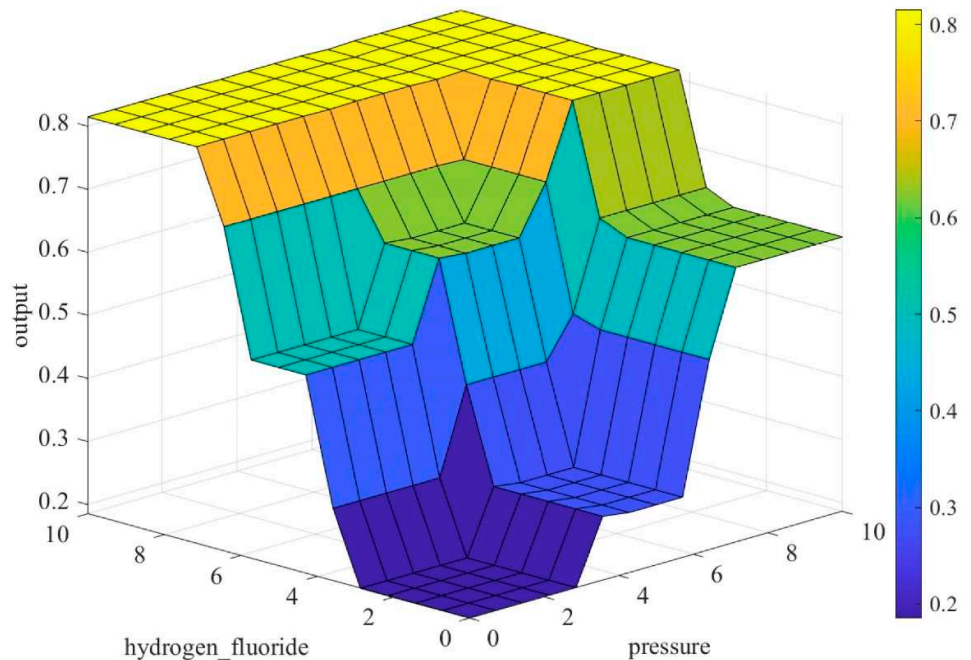


Fig. 5. Window surface of the output signal formed by the fuzzy correction module, when pressure and HF change, the input signal “CO₂” remains unchanged 3.5

5.3. Construction of a model of a sensor for early detection of thermal decomposition of the lithium-ion battery's internal filling

The SEDTD model was built in the Simulink package of the MATLAB environment. Let us investigate the operation of this sensor with a fuzzy correction module built using the Mamdani algorithm when input signals from pressure, CO₂ and HF concentration sensitive elements are supplied to the input. During the study, it was assumed that the input signals were scaled accordingly in such a way as to match the inputs of the designed fuzzy correction module (Fig. 6).

Fig. 7 shows the results of our study on the operation of SEDTD with a fuzzy correction unit when signals from pressure, CO₂, and HF sensitive elements are fed to its input.

From Fig. 7 it is seen that in the initial period of time the pressure, concentrations of CO₂ and HF are within the normal range. At the output of SEDTD, we have the “normal” mode. At the time $t \approx 23$ s, the pressure, CO₂ and HF begin to grow and the SEDTD switches to the pre-fire state mode (Im50%). When $t \approx 38$ s, the values of the pressure, CO₂ and HF reach critical values, the SEDTD switches to the “Fire” mode.

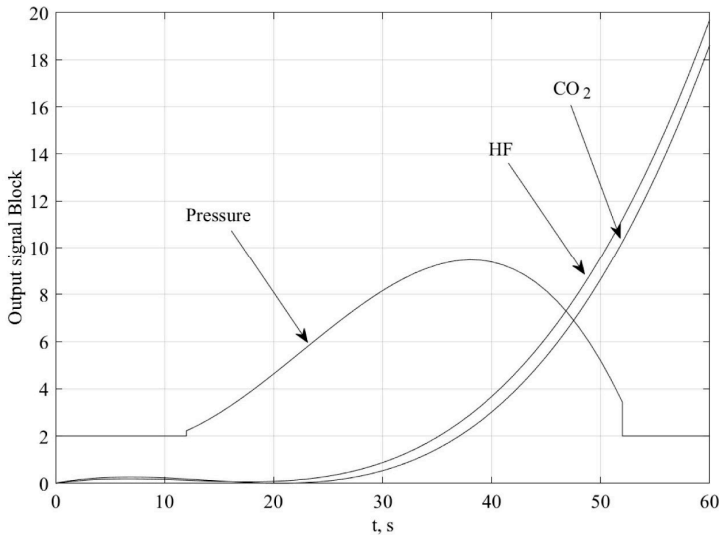


Fig. 6. Reduced input data from pressure, CO₂, HF sensitive elements

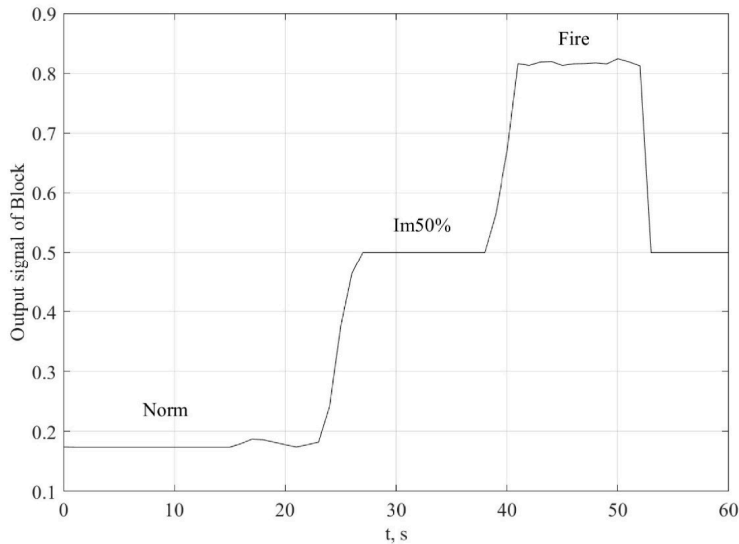


Fig. 7. Results of research into the operation of a sensor for early detection of thermal decomposition of a lithium-ion battery with a fuzzy correction unit

Thus, the results of digital modeling in Simulink/MATLAB show that the designed SEDTD with a fuzzy correction unit using the Mamdani algorithm with sensitive elements (sensors) for pressure, CO₂, and HF operates in accordance with the established operation algorithm.

6. Discussion of results based on defining the key parameters for thermal decomposition of a lithium-ion battery and the possibility of their determination

Intensive release of thermal decomposition products in a small volume of the battery directly leads to an increase in absolute pressure in the medium (P_{abs}). Taking into account the fact that the increase in the temperature indicators of LIB above 180°C will be accompanied by intense combustion, the main indicators of preliminary detection of thermal decomposition of LIB were determined to be a change in pressure (P_{abs}), an increase in the concentration of CO₂, CO. Additionally, the presence of substances such as HF is also determined as a factor in the onset of thermal decomposition

of LIB. The change in the concentration of the obtained indicators of CO₂, HF was shown in Fig. 1, 2, and the change in P_{abs} in Fig. 3. Accordingly, the maximum CO₂ concentration during thermal decomposition of one cylindrical LIB is within 80000–90000% ppm, HF is within 1000–1200% ppm, the change in pressure increase in the closed volume P_{abs} will be 250–300 kPa. Additionally, polynomial dependences of the change in the value of P_{abs} , and the concentration of CO₂, HF depending on the temperature indicators of LIB were obtained. They were used to monitor the current state of the battery and subsequent design of SEDTD for the internal filling of LIB.

Unlike earlier approaches and developments [8–11] for early detection of the onset of thermal decomposition of LIB, the SEDTD model was constructed in our work by using a fuzzy correction module synthesized employing the Mamdani algorithm. For this purpose, the fuzzy correction module itself was initially designed. Analysis of the surface of the output signal of the fuzzy correction module (Fig. 4, 5) reveals the presence of characteristic areas corresponding to different states of the system. For example, at low values of pressure and CO₂ concentration, the output signal acquires minimum values (blue area in Fig. 4), which corresponds to the linguistic term “Norm”. In the case of an increase in one or both parameters, a gradual increase in the output signal is observed, which is interpreted as a pre-fire state with a probability of 50% “Im 50%”. At simultaneously high values of pressure and concentration of CO₂ (Fig. 4) or high values of pressure and concentration of HF (Fig. 5), a region of maximum values of the output signal is formed, which corresponds to the term “Fire”. The shape of the surface has a nonlinear character with pronounced transitions between states, which is due to the use of fuzzy inference rules, aggregation operations and defuzzification procedures in the Mamdani algorithm. Such a structure reflects the complex interaction between input parameters and provides an adequate interpretation of intermediate

states. Thus, the output signal of the fuzzy correction module serves as an estimate of the current state of LIB.

Fig. 7 shows the time dependence of the output signal of SEDTD for LIB with a fuzzy correction module synthesized based on the Mamdani algorithm. The output signal is formed in response to a change in the input parameters of pressure, CO₂ and HF concentrations, the dynamics of which are shown in Fig. 6. In the initial period of time from $t = 0$ s to $t = 23$ s, the value of all controlled parameters is within the normal range. This corresponds to the stable operation of LIB. At the output of SEDTD there is a low signal level, which corresponds to the norm. Starting from the time $t \approx 23$ s, an increase in the pressure and concentration of CO₂ and HF gases is observed, which corresponds to the initial stage of thermal decomposition of the accumulator. During this period, the fuzzy system makes a transition to the pre-fire state, which corresponds to the linguistic term “Im50%”. Further increase in the input parameters leads to the achievement of critical values. At this moment ($t \approx 23$ s) there is a rapid transition of the output signal of SEDTD to a high level, which corresponds to the “Fire” signal. In the specified time interval, the SEDTD records a stable emergency state, which indicates the development of a dangerous process and the need for immediate response. At $t \approx 50$ s, a decrease in the initial state to the pre-fire state level is observed. This is explained purely theoretically because the concentrations of CO₂ and HF gases entering the SEDTD input are modeled according to equations (2) to (4), which describe the dependences in Fig. 1–3.

Thus, the given dependence demonstrates the capability of SEDTD with the fuzzy correction unit to be in different states depending on the complex analysis of input signals, which makes it possible to effectively identify the normal, pre-fire, and emergency modes of LIB operation.

Our result makes it possible to subsequently design a multi-channel SEDTD for LIB with the fuzzy correction unit on a microprocessor, in particular Arduino. The further complexity of the implementation of the specified device is the need to conduct additional research and design sensors capable of detecting insignificant concentrations of HF and changes in the absolute pressure of the medium, P_{abs} . A possible further solution to the specified difficulties is the use of neuro-interference technology and variations in the analysis of indicators using artificial intelligence technology.

Considering that the model was built based on experimental results [22] for LIB NCR 18650B other elements can emit different concentrations and chemical composition of thermal decomposition products during thermal decomposition. Accordingly, the application of the proposed model may be limited by the type of chemical filling of LIB and their format.

As a direct drawback of our study, one can note that the obtained indicators and the given dependences are a theoretically justified result, developed under the conditions of mathematical modeling. Accordingly, the proposed model should be further tested in the experimental research setting using the experimental sample of SEDTD for LIB.

7. Conclusions

1. The onset and evolution of the irreversible thermochemical reaction in LIB can be determined from the

results of identification, first of all, of the concentration of CO₂ and the increase in absolute pressure (P_{abs}) in the total volume of the thermal decomposition site of the internal filling of the element. An additional parameter for identifying thermal decomposition can be to determine the presence of HF. The corresponding indicators can be described by polynomial dependences of the third order, according to which the maximum value of CO₂ is determined within 80000–90000% ppm, the maximum value of HF within 1000–1200% ppm, the maximum value of P_{abs} within 250–300 kPa.

2. A fuzzy correction module using the Mamdani algorithm has been designed for a multi-channel SEDTD in LIB, the input of which is the value of the pressure parameters, the concentration of CO₂ and HF gases. The forms and parameters of the input and output membership functions have been established. A database of fuzzy rules describing possible states of the LIB has been compiled. Simulation in the Fuzzy Logic Toolbox package in the MATLAB environment qualitatively reflects the perception of input signals about the onset and evolution of thermochemical reaction.

3. A model of a multi-channel SEDTD for LIB has been built, which includes a fuzzy correction module in the Simulink package of the MATLAB environment. The results of simulation studies have confirmed the effectiveness of the proposed approach. It has been established that the sensor, based on a comprehensive analysis of input parameters – pressure, CO₂ and HF concentrations – forms an information output signal that adequately reflects the technical state of the LIB, in particular normal, pre-fire (pre-emergency), and fire (emergency) states. The proposed approach to building a sensor with a fuzzy correction module provides the possibility of reliable detection of changes in the composition of thermal decomposition products in LIB at the early stages of the evolution of hazardous processes. This, in turn, creates prerequisites for timely decision-making regarding fire prevention and effective localization of potential emergencies.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Andrii Kushnir: Software, Validation, Visualization;
Oleksandr Lazarenko: Project administration, Formal

analysis, Writing – original draft, Supervision; **Roman Tattsiy:** Writing – review & editing, Funding acquisition;
Oleh Bashynskiy: Resources, Funding acquisition; **Roman Aleshko:** Data Curation, Funding acquisition.

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