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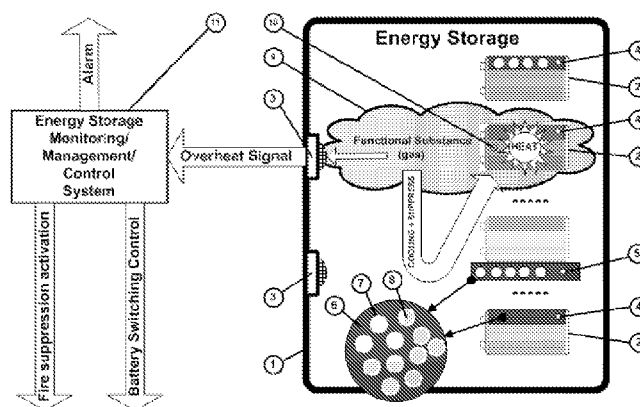


FIG. 1

(57) Abstract: The proposed lithium-ion energy storage system relates to the field of identifying heating and suppressing fires in lithium-ion batteries and comprises a plurality of lithium-ion battery cells, at least one gas detector and at least one functional structural component thermally linked to at least a part of an outer surface of each lithium-ion battery cell and made of material comprising a functional composite thermoreactive compound comprising microcapsules configured to break when heated to a specific critical temperature and filled with a functional substance in a liquid state, the functional substance comprising perfluoro(2-methyl-3-pentanone) and a filler enhancing thermal conductivity of the material.



ADVANCED FIRE SAFETY LITHIUM-ION ENERGY STORAGE SYSTEM EMPLOYING THE COMPOSITE THERMOREACTIVE MATERIAL

TECHNICAL FIELD

[0001] The present invention relates to the field of identifying an abnormal heating and suppressing fires in lithium-ion batteries as a part of electric energy storage systems, and can be applied in electric power generation installations with conversion of wind energy, solar energy, tidal energy and the like, stationary alternative power supply sources, as well as onboard electric power sources for vehicles enabling the conversion of electrical energy into propulsion, including electric cars.

[0002] Lithium-ion batteries represent a cutting-edge technology for electrochemical energy storage. However, due to their design, high energy density and materials used, they pose a heightened risk if proper production and usage conditions are not maintained as well as in case of damage due to emergency. This risk is further exacerbated by potential lapses in manufacturing quality, the materials used in production, and the natural aging of those materials.

[0003] The general trend of improving the energy characteristics of storage systems is associated with an increase in capacity and the speed of their charge and discharge, as well as the specific volume and mass density of the energy accumulated in the storage systems. However, these improvements lead to intensification of operating modes (increased charge and discharge regimes and operating temperatures) and design changes in the form of reduced structural gaps between the components of the storage system and batteries, use of modified materials with more stringent requirements for them, which leads to increase the risk of emergency situations and worsened safety in usage.

[0004] The increased danger is associated with the risk of fire and explosion of lithium-ion batteries caused by thermal runaway processes as a result of internal electrochemical reactions, and/or external factors in the form of improper operating and storage conditions, as well as force majeure circumstances, in particular, external mechanical impact as a result of emergency events. Storage systems with significant capacity, accumulating large volumes of energy and containing a large number of lithium-ion cells concentrated in a limited localized space are particularly dangerous.

[0005] It is worth noting that ignition of lithium-ion batteries is significantly different from other types of ignition, since lithium-ion batteries are a certain kind of energy object that has an internal ability of latent heating and self-ignition, and is also characterized by

high intensity and temperature of combustion, rapid heat spread, high toxicity of combustible materials, significant difficulties in extinguishing and the ability to reignite [«LIB fires pose hazards which are significantly different to other fire hazards in terms of initiation route, rate of spread, duration, toxicity, and suppression», Laura Bravo Diaz, Xuanze He, Zhenwen Hu, Francesco Restuccia, Monica Marinescu, Jorge Varela Barreras, Yatish Patel, Gregory Offer and Guillermo Rein. Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions. Journal of The Electrochemical Society, 2020 167 090559].

[0006] Despite the obvious significant progress in the development of lithium-ion energy storage technology in terms of mitigating the risks of accidents associated with thermal runaway, fire and explosion, including fully solid-state batteries, in the next few years the dominant solutions in the lithium-ion battery market will remain those using liquid electrolytes containing a certain amount of flammable organic solvents. Thus, the problem of reducing the risks of severe consequences of fire in lithium-ion batteries remains relevant.

[0007] In this regard, a significant factor in increasing the fire safety of lithium-ion batteries is the earliest possible detection/identification of the onset of the thermal runaway process.

[0008] It is known that emergency process in energy storage systems starts most often from thermal runaway of one single battery cell and then spreads to the battery block, and then to neighboring blocks [HUAWEI DIGITAL POWER TECHNOLOGIES CO., LTD, C&I ESS Safety White Paper <https://solar.huawei.com/download?p=%2F-%2Fmedia%2FSolarV4%2Fsolar-version2%2Fcommon%2Fprofessionals%2Fall-products%2Fother%2Fsnec-2023%2Fhuawei-c-i-smart-string-ess-safety-whitepaper.pdf>]. Taking this feature into account, the most difficult emergency situation to detect is the latent emergency process, characterized by minor change of controllable parameters of the battery cell state in the very initial phase, with its typical primary occurrence at the level of one individual battery cell in the storage unit, in which parameters for monitoring the general state of the storage unit, such as the overall average temperature, discharge/charge currents, voltage, IR radiation, emission of various gases as a result of thermal runaway, do not provide timely and reliable information about the onset of the emergency process due to small changes in these parameters and/or high background values of the monitored parameter in the initial stage of the process in the individual battery.

[0009] The risk of thermal runaway occurs for three main reasons. First, due to

possible defects in materials and manufacturing process while production. Second, defects caused by violations of the operating modes of energy storage systems, namely, exceeding the maximum operating conditions due to incorrect operation of external equipment, or defects arising as a result of physical impact on batteries in the form of hits, systematic vibration, external overheating, as well as thermal fatigue and degradation of materials due to aging. Third, chemical reactions of battery materials leading to changes in the characteristics of their components, in particular, degradation of the insulating properties of the battery cell separator and the growth of dendrites on the surface of the electrodes for some types of lithium-ion batteries. All these reasons can lead to an emergency process of thermal runaway and ignition of batteries and lithium-ion energy storage systems.

[0010] Specific risk factors for the fires in lithium-ion batteries and energy storage devices, in contrast to other devices, are:

[0011] - presence of an internal source of electrochemical energy and internal heat generation in the emergency mode;

[0012] - use of flammable organic materials (for example, electrolyte, electrode separator, and others);

[0013] - presence of combustible metals (lithium, aluminum) in their composition;

[0014] – release of hydrogen during thermal decomposition of organic materials and contact of lithium with water;

[0015] – release of oxygen during the decomposition of the battery cathode material.

[0016] Regardless of the cause of the emergency situation, in general there are three key time factors for increasing the safety of operation of energy storage systems based on lithium-ion batteries in the event of an emergency thermal runaway:

[0017] – as possible earlier detection of the onset of the thermal runaway process;

[0018] - possible impact on the process of thermal runaway to slow it down and hence to increase its development time;

[0019] - possible suppression of active combustion to slow down its transition to the phase of catastrophic development and spread of the fire.

[0020] It is commonly known that typical operating temperature of conventional batteries should not exceed 60°C. So, one of the most reliable indicator of the onset of thermal runaway, considering the acceptable margin of error in temperature measurement, is when the battery temperature exceeds 70-80°C.

RELATED ART

[0021] There are known technical solutions for detecting the heating of lithium-ion battery cells and energy storages based on sensitive elements like thermistors, thermocouples, thermistors, fiber-optic sensors based on fiber Bragg gratings, acoustic thermal sensors, IR radiation sensors, detectors of various associated gases.

[0022] In the majority of variants of various sensors can be utilized,, the most commonly for the purposes of collecting and processing information from the sensors there are used Battery Management Systems (BMS) and Battery Temperature Management Systems (BTMS), which are the means of detecting emergency failures in the operation of energy storage systems and, in particular, the thermal runaway process.

[0023] However, the practical applicability and reliability of such methods may be doubtful.

[0024] In one embodiment, such systems use secondary parameters (e.g., current and voltage) that allow the thermal state to be estimated indirectly based on a certain model of of the temperature and state of the battery cells and energy storage systems. Reliability of the detection is determined by the adequacy of the model used.

[0025] Another approach is to measure temperature using a number of direct temperature measurement sensors. The general limitation of this method is related to the number of sensors used that is practically possible for design reasons to ensure the depth of precise monitoring. For example, the temperature of an individual battery cell is the most accurate indicator that the battery cell is beginning to undergo an emergency heating process. However, equipping each individual battery cell with a sensor for measuring a meaningful information parameter with the corresponding circuits for connecting each sensor to energy system management units substantially increases the complexity of the system and drives up cost of the monitoring system. In addition, the use of a large number of sensors reduces overall reliability of the energy storage system, since the sensors themselves, as integral component of the system, in the event of a malfunction, are the source of abnormal operation mode of the energy storage system.

[0026] In the compromise version of a limited number of sensors of a meaningful information parameters, the detection of emergency heating of the battery cells does not reach the required tolerance of detection at the level of an individual battery cell and detection occurs at a too late stage of raising of the representative temperature of the energy storage or battery cell, when the temperature is already high and the available time for response to an emergency situation turns out to be unacceptably short for an adequate actions.

[0027] Another approach in detecting energy storage failure is based on the use of detectors of various gases (H_2 , CO , CO_2 , CH_4 , C_2H_4 , C_2H_6 , $n-C_4H_{10}$, etc.) emitted during thermal degradation of energy storage materials, and the detection of smoke and flame. The drawback of these approaches is that they relate to the detection of degradation and combustion resulting from thermal runaway, and not to the detection and/or prediction of the onset of thermal runaway, since they imply monitoring of parameters (in particular, detection of gases) associated with the late stage of the emergency process mostly in the phase of active combustion, and they definitely cannot be classified as technical solutions for early detection of the onset of thermal runaway. In addition, the application of these methods is limited by their low detection sensitivity at the initial stage of the process and significant influence of ambient background levels of the gases concentration) on sensitivity and selectivity.

[0028] A battery system with an early detection capacity for thermal events as well as the method for early detection of thermal events in a battery system, known from DE102020206474B3, and a battery system for a vehicle and method for detecting an overheat situation of the battery system, known from US10992013B2, were adopted as prototypes. The main disadvantages of the considered well-known technical solutions:

- the majority of known technical solutions for detecting emergency thermal runaway of lithium-ion energy storage systems do not cover the development of their practical implementation in mass production and use, which is a significant drawback or obstacle to their implementation;
- some of the known technical solutions suggest the use of active substances that are classified as hazardous to human health, such as cyclohexane;
- the known technical solutions do not solve overall combined problem of increasing the time available for evacuating people in the event of an emergency by slowing down the rate of temperature increase of a faulty lithium-ion battery cells in the energy storage system;
- the known technical solutions do not solve the problem of reducing the rate of increase of dangerous factors of ignition of energy storage devices and the development of an emergency situation by slowing down and partial suppressing the process of active combustion.

TECHNICAL TASK

[0029] The technical task of the present invention is to create an electric energy storage system based on lithium-ion battery cells with increased safety, achieved by the

earliest possible reliable detection of the occurrence of an emergency situation associated with thermal runaway, at the level of a single elementary battery cell and slowing down the rate of development of such an emergency situation in order to increase the available time for responding to the occurrence of this emergency situation and thereby increasing the overall safety of the electric energy storage system.

TECHNICAL SOLUTION

[0030] The technical task has been solved as follows.

Provided is a lithium-ion energy storage system comprising a plurality of lithium-ion battery cells mounted within a housing and at least one functional structural component thermally linked to at least a part of an outer surface of each lithium-ion battery cell, and made of material comprising a functional composite thermoreactive compound comprising microcapsules filled with a functional substance in a liquid state, the functional substance comprising perfluoro(2-methyl-3-pentanone), and the material filler enhancing its thermal conductivity. The microcapsules are configured to break when heated to a specific critical temperature in case of emergency heating of at least one lithium-ion battery cell and to release the functional substance, which then gasifies and to be further detected, then providing at least a partial cooling and/or fire suppression for the at least one lithium-ion battery cell. The lithium-ion energy storage system also comprises at least one gas detector configured to detect the functional substance in its gaseous phase within the housing and to generate a signal indicating the occurrence of emergency heating of at least one lithium-ion battery cell.

[0031] According to one embodiment of the present invention, the specific critical temperature is in a range of 70-140°C.

[0032] According to another embodiment of the present invention, the capsules are made to start breaking at a temperature in the range of 70 - 80°C.

[0033] According to another embodiment of the present invention, at least one functional component made of the material comprising the microcapsules is configured so that at least a portion of the microcapsules is thermally linked to at least a part of the outer surface of each lithium-ion battery cell, ensuring heat transfer from each lithium-ion battery cell to a portion of the microcapsules.

[0034] According to another embodiment of the present invention, the functional substance is perfluoro(2-methyl-3-pentanone) or a mixture of perfluoro(2-methyl-3-pentanone) with at least one auxiliary halogenated organic chemical compound, selected from hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons,

perfluoropolyethers, hydrofluoroethers, hydrofluoropolyethers, chlorofluorocarbons, bromofluorocarbons, bromochlorofluorocarbons, iodo fluorocarbons, hydrobromofluorocarbons, hydrobromocarbons, or fluorinated ketones.

[0035] According to another embodiment of the present invention, a volume of the functional substance in the microcapsules within the at least one functional component, when a portion of the microcapsules is heated to the predetermined critical temperature in case of emergency heating of at least one lithium-ion battery cell within the lithium-ion energy storage system and after release of the functional substance as a result of the destruction of the microcapsules shell, provides a volume of the functional substance in its gaseous phase within energy storage system housing sufficient for detection by the at least one gas detector.

[0036] According to another embodiment of the present invention, the functional composite thermoreactive compound further comprises a cold-curing polymer binder configured to fix the microcapsules within the energy storage system.

[0037] According to yet another embodiment of the present invention, the at least one functional structural component is configured as a coating of at least a part of each lithium-ion battery cell, wherein the coating comprises the microcapsules and a cold curing binder to attach the microcapsules to at least a part of the outer surface of each lithium-ion battery cell, as its structural component, to ensure that a sufficient portion of the microcapsules is thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

[0038] According to another embodiment of the present invention, the at least one functional structural component is configured as at least one film or at least one insert, made of material including the functional composite thermoreactive compound, ensuring that sufficient portion of the microcapsules are thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

[0039] According to yet another embodiment of the present invention, the at least one structural component is designed to fix lithium-ion battery cells within the lithium-ion energy storage system and is configured as a pouring filler made of the material filled with the microcapsules with functional substance, ensuring that the sufficient portion of the microcapsules are thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

[0040] According to another embodiment of the present invention, the material of the functional structural component comprises the filler enhancing thermal conductivity of the material in an amount of 30-70% of a total mass of the functional composite

thermoreactive compound in the material content for at least one of the at least one functional structural component.

[0041] According to another embodiment of the present invention, the at least one gas detector is connectable to an external control and alarm system.

ADVANTAGEOUS EFFECTS OF THE INVENTION

[0042] Due to the specified set of essential features of the claimed invention, it has become possible to detect at early stages an emergency condition of a lithium-ion energy storage system by identifying emergency heating at the level of each individual battery cell in its composition, as well as to slow down the thermal runaway process due to the cooling effect of the functional substance during its release from the microcapsules and the phase change from a liquid to a gaseous state and to suppress the combustion of the decomposition products of the energy storage system materials in the volume of its housing by the functional substance with a cooling effect due to a radicalization reaction, which slows down the rate of development of an emergency situation and increases the available time to respond to the occurrence of this emergency situation and, thereby, increases the safety of the electric energy storage system.

[0043] Moreover, due to the fact that microcapsules with a functional substance are in thermal contact with each battery of the energy storage system, detection of emergency heating occurs at the level of each battery cell individually, which significantly increases the reliability of detecting the onset of such heating, since in the event of thermal runaway of any of the battery cell in the energy storage system, the functional substance evaporates in sufficient volume into the space of its housing and is detected by a functional substance detector in the gas phase, which forms an information signal of the occurrence of the thermal runaway process. It should be noted that due to the fact that the lithium-ion energy storage system contains at least one functional component containing a composite thermoreactive material, which, in its turn, contains a binder and microcapsules filled with a functional substance in the liquid phase, including perfluorine (2-methyl-3-pentanone), in order to detect an emergency condition of the lithium-ion energy storage system at early stages, it is sufficient to ensure thermal contact of at least one functional component with at least part of the outer surface of each lithium-ion battery. Moreover, the emergency state of the lithium-ion energy storage system is reliably determined at early stages of emergency heating of any out of plurality of battery cells.

Depending on the specific design of the energy storage system, the number of detectors of the functional substance can vary down to the minimum required one

detector. The possibility of using at least one gas detector for reliable determining emergency heating of any out of a plurality of battery cells at early stages is ensured, in particular, by using the specified at least one functional component in the lithium-ion energy storage system structure. The ability to implement the technical solution function with a minimum number of detectors increases the overall reliability of the energy storage system as an integral system by reducing the total number of components.

[0044] Simultaneously with the above-mentioned technical result, a slowdown in thermal runaway is also achieved by cooling the emergency battery cells through absorbing the heat released by them for gasification of the functional substance when microcapsules open, which reduces the speed of the emergency battery temperature raise and increases the time from the moment of detection of the functional substance in the volume of the energy storage system housing, associated with thermal runaway, till the moment of the temperature increase to the level of the critical ignition temperature of the energy storage system materials, usually amounting to 150-220°C, and the transition of emergency process to the phase of intense combustion and/or explosion.

[0045] An important addition to the above results in the claimed invention is the provision of a partial interruption or complete termination of the combustion reaction of the energy storage materials, happening under the influence of their thermal decomposition at a temperature above 150-220°C and ignition.

[0046] Another important factor influencing the battery cell thermal emergency process is that during the transition phase of the thermal runaway to open combustion due to burn of ejected flammable substances, the temperature in the area of emergency battery increases significantly to a temperature of 400°C or more. At the same time, perfluorine (2-methyl-3-pentanone) molecules decompose at this high temperature with the formation of free fluorine radicals.

[0047] These free radicals capture the combustion radicals generated from organic substances of battery cell components while heated above 400°C, which causes inhibition of the combustion chain reactions to extinguish fire. In addition, there is the effect of reduction of the oxygen concentration in the fire and oxygen isolation from contacting with the active radicals, and thus to inhibit the free radical chain reactions in the combustion.

[0048] Moreover, the process of breaking and formation of chemical bonds at the thermal decomposition of perfluorine (2-methyl-3-pentanone) happens in format of endothermic reaction with considerable heat absorption. Energy characteristics of these processes are extremely complicated.

[0049] The specific dissociation energy of the C-F chemical bond while formation of a fluorine radical for the CF₄ molecule, which one is close to the structural component of the perfluoro(2-methyl-3-pentanone) molecule, is 540 kJ/mol. Thus, the dissociation energy of each of 12 C-F bonds for the perfluoro(2-methyl-3-pentanone) molecule is about 2000 kJ/mol.

[0050] For the battery cell 18650 form-factor coated by functional composite thermoreactive compound comprising microcapsules filled with the functional substance of perfluoro(2-methyl-3-pentanone) in amount of 2 g delivers estimation of 150 kJ heat absorption causing temperature decrease in assumption perfluoro(2-methyl-3-pentanone) gasified completely and all C-F bonds are dissociated.

[0051] The decrease in temperature will reduce the burning chain reaction velocity or even demolish the conditions of the combustion at all and terminate fire propagation. That at least slow down emergency process to increase available time for evacuation or terminate it completely to improve energy storage safety.

[0052] The combination of the above results in the form of a comprehensive technical solution increases the time interval from the moment of identification of the beginning of the process of emergency thermal runaway of the first battery cell with the maximum possible and sufficient depth of detection of the emergency situation at the level of one faulty battery until the moment of transition of the emergency process to the phase of intensive active combustion or explosion with a large release of heat and the development of an emergency situation on neighboring batteries in the energy storage system and the energy storage system as a whole, as well as other neighboring objects, which significantly increases the safety of using energy storage systems based on lithium-ion batteries.

[0053] It is worth noting that the closest known technical solutions do not set a comprehensive task of detecting the onset of thermal runaway, slowing down the process of thermal runaway and combustion suppression, but they only declare the effect of detecting the heating caused by thermal runaway. In other words, known technical solutions do not solve the problem of achieving a triple technical effect: "detection" - "slowing down of heating" - "suppression of combustion" in one single technical solution, applied to lithium-ion energy storage systems to achieve the goal of increasing the time from the moment of detecting the onset of the thermal runaway process to the catastrophic development of an emergency situation in order to improve safety within the framework of a single integrated technical solution, while this problem is solved by the present invention.

BRIEF DESCRIPTION OF DRAWINGS

[0054] Fig. 1 shows a structural diagram of a lithium-ion energy storage system.

[0055] Fig. 2 shows a structural diagram illustrating the achieved technical result.

[0056] Fig. 3 shows a battery cell with a cylindrical body, on the surface of which microcapsules are applied.

[0057] Fig. 4 shows a battery cell with a cylindrical body, on the surface of which self-adhesive pad is applied, the material of which includes microcapsules in the form of a filler.

[0058] Fig. 5 shows plate inserts made of thermoreactive material in the energy storage system housing.

[0059] Fig. 6 shows a prefabricated insert made of thermoreactive material in the form of a honeycomb structure in the housing of the energy storage system.

[0060] Fig. 7 shows a thermoreactive material in the form of a pouring compound in the energy storage system housing.

[0061] Fig. 8 shows TGA sample results for various shell materials.

[0062] Fig. 9 shows TGA of the thermoreactive material used in the experimental study of the technical solution.

[0063] Fig.10 shows a structure of the laboratory setup for testing the detection of functional substance.

[0064] Fig. 11 shows average detection response rate diagram.

[0065] Fig.12 shows a structure of the laboratory setup for testing the cooling effect of thermoreactive material.

[0066] Figure 13 shows a cooling effect diagram: test sample vs. calibration sample temperatures.

[0067] Fig. 14 shows a diagram of the cooling effect: the temperature of the test sample vs. the calibration sample (magnification).

DESCRIPTION OF EMBODIMENTS

[0068] The present invention proposes a design of a lithium-ion energy storage system with improved safety characteristics, one embodiment of which is described below with reference to Figs. 1-14.

[0069] The lithium-ion energy storage system (Fig. 1) consists of a housing 1, inside which a plurality of single-element lithium-ion battery cells 2 are placed and secured together, and at least one gas detector 3 is installed. In the energy storage

system housing 1, functional components are made of a composite thermoreactive material of triple action in the form of a coating 4 or independent structural components 5 having thermal contact with the housings of each of the battery cells 2. The functional components 4, 5 are realized of thermoreactive composite material including a binder 6 and microcapsules 7 filled with a functional substance 8 in the liquid phase, including perfluoro(2-methyl-3-pentanone). Microcapsules 7 are designed to break when heated to a specified critical temperature in the range of 70-140°C, preferably in the range of 70 - 80°C, and release a functional substance into the internal space of the energy storage system housing 1, followed by gasification of this substance 9. According to this embodiment of the present invention, a portion of the microcapsules 7 is thermally linked to a part of the outer surface of each lithium-ion battery cell 2, ensuring heat transfer from each lithium-ion battery cell 2 to a portion of the microcapsules 7, however, according to other embodiments it is also possible that all microcapsules are thermally linked to entire outer surface of each lithium-ion battery cell. It is important to note that in other embodiments the functional substance can be a composition of primarily perfluoro(2-methyl-3-pentanone) with at least one auxiliary halogenated organic chemical compound, selected from hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons, perfluoropolyethers, hydrofluoroethers, hydrofluoropolyethers, chlorofluorocarbons, bromofluorocarbons, bromochlorofluorocarbons, iodofluorocarbons, hydrobromofluorocarbons, hydrobromocarbons, or fluorinated ketones in a mixture.

[0070] The gas detector 3 is designed with the possibility of detecting a functional substance in the gas phase and is connected to an external control and signaling system 11 of the energy storage system.

[0071] In the event of the start of an emergency heating process of any of the battery cell 2 due to emergency thermal runaway, the functional component made of thermoreactive material is heated to a critical temperature, as a result of which the shell of the microcapsules 7 is destroyed under the influence of internal partial pressure and the functional substance 8 is released from the microcapsules 7 into the space of the energy storage system housing 1 with phase change from liquid to gaseous. A volume of the functional substance of the destructed microcapsules 7 after its release from at least one functional component is sufficient for detection by the at least one gas detector 3.

[0072] The released functional substance 8 in the gas phase 9 is detected by detectors 3 when the concentration in the volume of the energy storing system housing 1 reaches the level, which is sufficient for detection, and the gas detector 3 generates a useful information signal about the occurrence of an emergency situation in the form of

heating of an individual or several batteries.

[0073] When the functional substance 8 is released from the microcapsules 7 and its phase transition from liquid to gas occurs, the energy released due to the thermal runaway of the emergency battery cell 10 is absorbed, and the speed of temperature increase in the battery 10 is reduced, which slows down the development of the emergency process as a whole.

[0074] With further development of the process, in the event of the impossibility of complete suppressing the temperature runaway of the emergency battery cell 10, its temperature may reach the level of degradation and ignition of the materials contained in the battery 2 and adjacent structural elements of the energy storage system and their ignition. In this case, the functional substance 8, which released from the microcapsules 7 into the inner space of the energy storage system, suppresses combustion due to its fire extinguishing properties, which leads to a slowdown in the development of the emergency process and the spread of combustion at least and increases by that the time from the start of thermal runaway to the stage of dangerous active combustion and/or explosion.

[0075] The proposed technical solution allows to improve the safety characteristics of the energy storage system in case of emergency thermal runaway of any individual battery cell 2 in its structure, due to early detection of the emergency process and reduction of the process development speed at least and to get extended time from the moment of its first detection until the onset of catastrophic phase development, and to take additional possible actions to suppress the process thanks to usage of the functional thermoreactive substance 8, which has a triple effect (Fig. 2).

[0076] It turned out that the use in the proposed technical solution of one or more functional components containing a composite thermoreactive material, which contains a binder 6 and microcapsules 7 filled with a functional substance 8, makes it possible to detect emergency heating of any individual battery cell 10 at early stage, but not at the late phase of further development of the emergency situation, when heat from this battery cell 10 is already transferred to neighboring batteries 2, even when this one or more functional components have thermal contact only with a part of the outer surface of the emergency battery cell 10, and also to ensure more effective cooling of the emergency battery 10 and more effective slowing down of the process of its thermal runaway and combustion. It also turned out that in the proposed technical solution it is possible to use one gas detector 3 for sufficiently reliable determination of emergency heating of any out of plurality of batteries at early stages.

[0077] The storage system housing 1 is a hollow, conditionally-hermetic structure, inside which the battery cells are placed, and designed to protect the battery cells in the energy storage system from the impact of environmental factors such as dust, moisture and temperature, as well as physical damage to the batteries and internal components of the storage system structure and electrical insulation of the conductive elements of the energy storage system that are under voltage. The housing can be made of various structural materials, such as aluminum alloys or composite materials based on various synthetic chemical compounds.

[0078] The battery cells 2 can have various body shapes, in particular, cylindrical, prismatic or pouch. The shape of the battery cell body is not of a fundamental importance and the claimed invention is applicable to all known shapes of battery bodies. It is important that the body of each battery cell at least partially thermally conducted to the functional components 4 or 5.

[0080] Microcapsules 7 can be placed inside the energy storage system housing 1 in various design options.

[0081] In one embodiment, microcapsules 7 can be placed in the form of a coating 4 with a filler for the coating base that is applied to the outer surface of the battery cell 2 body with a thickness of 500-1000 μm , as in conventional painting process.

[0082] In another embodiment, microcapsules 7 are applied by spraying in 1-2 layers onto an adhesive substrate, previously applied to the surface of the battery cell body 2 to form the functional component 4 (Fig. 3).

[0083] In another embodiment, microcapsules 6 are attached to the surface of the battery cell body 2 in the form of a self-adhesive film or patch (Fig. 4), the material they made of includes microcapsules 7, in the form of the film or patch material filler while the film or the pad manufacturing, and this functional component attached to the body of batteries 2 prior their assembling in the energy storage system housing 1.

[0084] These methods of placing functional thermoreactive material inside the energy storage system are most appropriate to use at the stage of production of elementary battery cells 2.

[0085] In another embodiment, microcapsules 7 are placed in the material of a pre-fabricated insert 5 in the energy storage system housing 1, which is an integral structural component of the energy storage system, having a plate-like (Fig. 5) or a pre-fabricated specific shape, for example, a honeycomb structure (Fig. 6).

[0086] In another embodiment, microcapsules 7 are placed in the energy storage system housing 1 in the form of self-sustained thermoreactive composite pouring

compound 5 filled with microcapsules as well as a thermoreactive composite additive to general purpose pouring compound, when both functionally work as reinforcement structural element for fixing batteries 2 in the storage system housing 1 (Fig. 7).

[0087] These methods of placing thermoreactive material are the most appropriate to use at the stage of production of assembled energy storage systems.

[0088] An important factor in the effectiveness of the present invention to achieve the goal is to ensure efficient heat transfer from the lithium-ion battery cell body to the functional structural component and overall dissipation of heat from the surface of the lithium-ion battery cell through the functional structural component made of thermoreactive composite material to the ambient space to prevent overheating in normal operational mode and to reduce temperature rise speed in event of emergency thermal runaway. Thermal insulation of the lithium-ion battery cell in general might provoke a more intensive thermal runaway process and speed up catastrophic development of emergency situation.

[0089] Most of the known composites that can be used as a cold-curing binder to prepare a thermoreactive functional compound are organic substances and have relatively low thermal conductivity. In particular, in one of the possible and preferred applications of silicone rubber, this index is about 0.15-0.25 W/mK.

[0090] To achieve more efficient heat transfer, it is also proposed to use a filler enhancing thermal conductivity of the thermoreactive material, of which the functional structural components are made. In some embodiments of the present invention, the thermoconductive filler of the thermoreactive material enhancing thermal conductivity, represents, for example, but not limited to, finely dispersed fractions of boron nitride, graphite, graphite tubes, graphene, aluminum oxide Al_2O_3 , zinc oxide ZnO , or their combinations. Use of such additional filler in amount of 30-70% of the total mass of the thermoreactive compound makes it possible to achieve thermal conductivity at a level of 1.2-4.0 W/mK, which means that the thermal conductivity of the thermoreactive material itself and the components made of it increase by 6-20 times.

[0091] Another important technological factor is that, when producing structural components from materials filled with microcapsules 7, cold-curing chemical compounds must be used as a binder 6, since, during the production of these structural components, the microcapsules 7 must not be heated above 50°C to ensure that their properties are preserved. For example, compounds based on silicones, polyurethanes, epoxy, glyphthalic, pentaphthalic, alkyd, organosilicon or polyorganosiloxane resins can be used. It is essential as well that the binder should not contain water as a solvent or be based

on an aqueous emulsion of polymers, since the presence of water can lead to injury of the integrity of microcapsules.

[0092] The functional substance 8 is based on application of perfluoro(2-methyl-3-pentanone) as the main component or in its mixture with at least one of the auxiliary halogenated organic chemical compounds selected from the group consisting of hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons, perfluoropolyethers, hydrofluoroethers, hydrofluoropolyethers, chlorofluorocarbons, bromofluorocarbons, bromochlorofluorocarbons, iodofluorocarbons, hydrobromofluorocarbons, hydrobromocarbons, as well as other fluorinated ketones.

[0093] The choice of a chemical compound used as a functional substance 8 in microcapsules 7 is defined by the specific properties of the chemical compound or a mixture of compounds appropriate for the purposes of the invention.

[0094] The general criteria for selecting a chemical compound as the functional substance are as follows:

[0095] - boiling and evaporation temperature;

[0096] - low background values of concentration in ambient air;

[0097] - availability of reliable and easy detection tools;

[0098] - ability to suppress combustion;

[0099] - dielectric properties;

[0100] – compatibility with microencapsulation technology;

[0101] - environmental safety.

[0102] In various embodiments, in general, halogenated organic chemical compounds can be used as the functional substance 8.

[0103] Based on the combination of selection criteria and the main criterion – the boiling point, the most promising seems to be the use of perfluoro(2-methyl-3-pentanone) as a functional substance, which has a boiling point in pure form of 49.2 °C.

[0104] In more detail for the practical implementation of the invention, it is preferable to use perfluoro(2-methyl-3-pentanone) due to the following reasons:

[0105] 1. Taking into account the boiling point, the release of perfluoro(2-methyl-3-pentanone) from the thermoreactive material containing microcapsules 7 occurs the most intensively in the temperature range of 80-140°C, which corresponds to the goal of early detection of overheating of battery cells 2 to the required extent and provide minimization of false alarms probability.

[0106] 2. The boiling point of perfluoro(2-methyl-3-pentanone), in contrast to similar compounds with a lower boiling point, the best way corresponds to known modern

technologies of microencapsulation of low-boiling chemical compounds.

[0107] 3. Perfluoro(2-methyl-3-pentanone) is a fully synthesized chemical compound with minimal presence in the ambient space, that allows the use of the detector 3 of this compound with high sensitivity and high selectivity, which contributes to the overall sensitivity of overheating detection and minimization of false alarms.

[0108] 4. Perfluoro(2-methyl-3-pentanone) is an environment friendly substance, in particular it has an ozone depletion potential (ODS) of zero and global warming potential (GWP) less than 1 and meets the requirements of Kyoto Protocol and Montreal Agreement, it does not belong to the category of 'greenhouse gases' and it is safe in terms of destruction of the Earth's ozone layer, and it is also non-toxic. The natural decomposition of perfluoro(2-methyl-3-pentanone) in the Earth atmosphere occurs under the influence of ultraviolet radiation with an average decomposition time of about 5 days.

[0109] 5. Perfluoro(2-methyl-3-pentanone) is a non-flammable chemical compound and does not increase the overall flammability of the energy storage system or support combustion.

[0110] 6. Perfluoro(2-methyl-3-pentanone) in the liquid phase has high dielectric properties and is safe for use in high-voltage electrical systems.

[0111] 7. Perfluoro(2-methyl-3-pentanone) has an additional positive effect, which consists in the fact that when microcapsules 7 are destroyed, its evaporation goes on as an endothermic process absorbing heat energy generated as the result of thermal runaway of the battery 2 and the heat transfer from the emergency battery to neighboring batteries is reduced.

[0112] 8. Perfluoro(2-methyl-3-pentanone) has a significant positive effect of suppressing combustion and slows down the process of battery cells combustion development in the initial phase.

[0113] Perfluoro(2-methyl-3-pentanone) can be used in pure form as the main functional substance 8, or in the form of a mixture with other chemical compounds used as auxiliary substances, in various proportions for the purpose of changing the physical and chemical properties, in particular the boiling point and transition to the gaseous phase.

[0114] Compositions of perfluoro(2-methyl-3-pentanone) with at least one of the halogenated organic chemical compounds selected from the group consisting of hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons, perfluoropolyethers, hydrofluoroethers, hydrofluoropolyethers, chlorofluorocarbons, bromofluorocarbons, bromochlorofluorocarbons, iodofluorocarbons, hydrobromofluorocarbons,

hydrobromocarbons and fluorinated ketones in various proportions in the range of 3-8% by weight of perfluoro(2-methyl-3-pentanone), which are auxiliary functional substances that change the boiling point of the main functional substance 8 optionally in the range from 0°C to 110°C while maintaining detectability, cooling and fire extinguishing properties, can be used. This temperature range is certainly wider than the required for detecting thermal runaway of lithium-ion batteries for the purposes of the present invention.

[0115] The selection of a specific auxiliary functional substance for changing the opening temperature of microcapsules 7 is determined by the requirements of the critical temperature level of specific energy storage system and the battery cells 2 in the energy storage system for safe operation and to achieve the purpose of the invention and applicability for implementation.

[0116] The release temperature of the functional substance 8 from the microcapsules while overheating, besides boiling temperature, is also influenced by the material and manufacturing technology of the shell.

[0117] Microcapsules 7, manufactured using the most common microencapsulation technologies, have a phase transition in the form of opening upon heating in the temperature range required for the purposes of the invention (Fig. 8).

[0118] In this case, the selection of the composition of the functional substance 8 and the shell material of the microcapsules 7 makes it possible to achieve the opening of the microcapsules 7 at the required critical temperature of the thermoreactive material. In the microencapsulation technologies the gelatin, urea-resorcinol-formaldehyde resins, melamine-formaldehyde resins, carbamide-formaldehyde resins, as well as polyurea-urethane resins and their combinations are used as the base material for the shell.

[0119] Since the functional thermoreactive component 4 of the lithium-ion storage system, in addition to the filler of microcapsules 7 with a specific opening temperature, includes an auxiliary binder 6 in the form of an adhesive or compound, this binder, taking into account the properties of its material and application technology, can also influence the change in the phase transition temperature of the functional substance 8.

[0120] Thus, the criteria for selecting the technology for forming the thermoreactive material and design of the structural components made from it are the properties of the functional substance 7, the technology and material for producing the microcapsules 7 and the properties of the material of the auxiliary binder that are most suitable for the specific implementation and obtaining the properties that specialists in this field of technology strive to achieve using the ideas disclosed in this document.

[0121] In the tests conducted, microcapsules 7 are spheres with a diameter of 150-300 μm with an average mass content of the functional substance of 85-95%.

[0122] The thermogravimetric analysis (TGA) diagram of the characteristics of this thermoreactive material is shown in (Fig. 9). The results of thermogravimetric analysis show that the opening of microcapsules 7 in the test sample began at the temperature of about 70°C, which corresponds to the purpose of the problem being solved.

[0123] The practical results of testing the thermoreactive material using the above-described microencapsulated functional substance 8 and the auxiliary silicone-based binder 6 are given in the description of the experimental studies conducted below.

[0124] Of great importance for the purposes of the invention is the parameter of the background concentration level of the functional substance 8 in the ambient air at the location of the batteries. This ensures the possibility of reliable detection of functional substance 8 in low concentrations with minimization of false cases, in particular, reliable detection by the selected type of sensor. The proposed functional substance 8 perfluoro(2-methyl-3-pentanone) can present in the ambient air only in the form of a fully synthesized artificial chemical compound. In addition, the decomposition period of perfluoro(2-methyl-3-pentanone) in the air atmosphere as a result of photolysis occurs within approximately in 4.5 – 15 days. Thus, the real possible background concentrations of perfluoro(2-methyl-3-pentanone) in the controlled zone in the space of the energy storage system during its normal operation are practically equal to zero.

[0125] From the point of view of practical implementation of the invention, another very important selection criterion is the availability of industrial level developed technological processes for microencapsulation of the functional substance 8 and its mixtures.

[0126] An additional important factor in the selection of functional substance 8 from the point of view of the practical implementation of the technical solution is its environmental safety. According to published data and testing results, perfluoro(2-methyl-3-pentanone) has:

[0127] - zero ozone depletion potential (ODP);

[0128] - global warming potential (GWP) less than 1.

[0129] - exceptionally low overall levels of 'greenhouse gas' emissions;

[0130] - exceptionally high toxic safety.

[0131] Another important component of the proposed energy storage system is a gas detector 3 for detecting the functional substance 8.

[0132] The functional substances proposed for use in the invention belong to the

class of halogenated organic chemical compounds. Taking this into account, for the purposes of detecting functional substance 8, the systems should react to the presence of halogens in the ambient air in the controlled space, and in particular fluorine.

[0133] Devices for detecting and measuring the concentration of halogens in the air are based on various detection methods, such as infrared spectroscopy, ion chromatography, fluorescence spectroscopy, ion-mobility analysis method, nanotube and spiropyran skeletal base and others, which can be used.

[0134] The use of the devices and sensors implementing such detection methods for the purposes of the invention is most often irrational due to technical complexity and unreasonably high cost for mass application in monitoring energy storage systems based on lithium-ion batteries, especially in the conditions of a typical limited monitoring space in application for mobile monitoring objects.

[0135] In general, gas detector 3 must have sufficient sensitivity to detect fluorine in the volume of free internal space of the energy storage system housing; the mass and dimensions of the detector must be minimal, taking into account the dense saturation of the energy storage system housing with batteries and other structural components.

[0136] The most rational for the purposes of the invention, in the opinion of the authors, but not limited to this, is the use of detectors based on semiconductor sensitive elements technology, for example, based on silicon dioxide (SnO_2).

[0137] The detectors of the proposed type have the required sensitivity starting from 10 ppm, are miniature, widely available at the open market and have a low cost compared to other types.

[0138] Most commonly, widely available industrial detectors do not have exceptional selectivity in response to fluorine, react to a group of halogens, and are broadband. However, this is not a significant negative factor for the implementation of the present invention.

[0139] Based on the above considerations, a TGS 832-A00 chlorofluorocarbon sensor from Figaro Engineering Inc. was used for testing, with a minimum stated sensitivity according to the specification equal to 10 ppm.

[0140] An additional result of the tests conducted is that the practical feasibility and possibility of achieving sufficient sensitivity for detecting functional substance 8 within the framework of the proposed technical solution have been proven, even based on the use of a cheap version of a mass-produced non-specific sensor.

[0141] The studies of the practical possibility of detecting the functional substance 8 were conducted using a laboratory setup (Fig. 10), including an energy storage

monitoring/management/control system 11 and a test chamber 12 with a volume of 15 liters, in which a test sample 13 in the form of a simulator of a battery cell 18650-form-factor with a thermoreactive coating 4 containing the functional substance, a sensitive element - a functional substance detector 3 of the functional substance 8 based on a TGS 832-A00 gas sensor, a power supply control unit 16 for heating the simulator 13, signal converters 17 and 18 of a temperature sensor 15 and a gas detector 3, and the signal data recording module 19.

[0142] The battery simulator 13 is an aluminum cylinder with geometric dimensions corresponding to the dimensions of the 18650 form factor battery cell (D=18 mm, L=65 mm). Simulator 13, in terms of weight (49.5 g) and thermal-physical characteristics of the material (Aluminum), is sufficiently similar for the purposes of evaluation tests to a generalized geometric and thermodynamic model of a real 18650 battery cell.

[0143] Heating of the simulator 113, simulating battery cell with thermal runaway, was carried out using a silicon semiconductor heating element integrated into the body of the simulator. The heating power was stabilized by the power control unit 16 at the level of 15W electric power, which corresponds to the estimated average thermal runaway power of the 18650 battery cell with capacity of 3500 mAh. The need to stabilize the heating power is associated with the positive temperature coefficient (PTC) of the ceramic heating element used and the need to offset the influence of PTC on the sample heating process.

[0144] A K-type thermocouple 15 was used as a temperature sensor, also integrated into the body of the simulator 13 and connected to the conventional signal converter 17.

[0145] The purpose of the study was to qualitatively confirm the declared functionality of the energy storage system in respect of detecting a functional substance when a standard-sized battery coated with a functional thermoreactive material is heated to the specific critical temperature.

[0146] For evaluation purposes, the lateral surface area of an 18650 form factor lithium battery cell is about 37 cm². When microcapsules 7 with functional substance 8 are placed in one layer with average thickness of 1000 µm on the lateral surface of the battery cell 2 of that format and applying the coefficient of volumetric filling value of a single-layer coating with functional substance as of 0.7 adopted for the evaluation calculation, 2.6 cm³ of encapsulated functional substance 8 is placed on lateral surface. This volume of capsules contains about 2.34 cm³ of pure functional substance in liquid form weighting 3.74 g.

[0147] In assumption of complete evaporation of functional substance 8 weighting 3.74 g in a space of of 1 m³ volume, calculated level of concentration of functional substance 8 in this volume in the gas phase reaches 700-800 ppm, which significantly exceeds the practically detectable minimum concentration levels of halogen-containing chemical compounds by recommended detectors. On the other hand, taking into account the achievable sensitivity of detectors of about 20 ppm, the presence of functional substance 8 in a volume of 1 m³ can be detected by collapse of 1% of the microcapsules with the functional substance located on the lateral surface of one 18650 battery cell in one layer.

[0148] The statistically processed results of a series of tests of the possibility of practical detection of the functional substance, carried out using the described laboratory setup, are presented at the diagram (Fig. 11).

[0149] These experimental results confirm the fairly reliable detection of heating of thermoreactive functional substance at the test sample temperature of 73 – 78°C using a conventional chlorofluorocarbon detector. Moreover, in 100% of tests in the series, functional substance 8 was detected at temperatures below 107°C, which confirms the effectiveness of the proposed solution for overheating detection.

[0150] In order to qualitatively confirm the effect of cooling the battery cell as a result of the evaporation of the functional substance 8 upon opening of the microcapsules 7, a series of tests were carried out using the laboratory setup shown in the diagram (Fig. 12).

[0151] The difference between the laboratory setup for this series of tests and the one described earlier is that the test chamber contains two battery simulators - test one 13 and calibration one 20, a power control unit 16, which, in addition to controlling of the heating power, balances the power of the test 13 and calibration 20 samples, two thermocouples 15, signals converters 17 for each sample and a two-channel temperature data log recording unit 19.

[0152] In a series of experiments, a thermoreactive coating 4 was applied to test sample 13 in two binder variants (organic silicon varnish KO-85 and silicone adhesive sealant AS1420) and comparative tests were conducted on the speed of temperature increase of the samples when they were heated by equal electric power.

[0153] It should be noted that during the experiments no significant differences were found in the results obtained for the two binder variants used.

[0154] The combined statistically processed results are presented in the diagram (Fig. 13) and its enlarged image (Fig. 14). Fig. 14 illustrates that by using a thermoreactive

material: a temperature shift of $\sim -7^{\circ}\text{C}$ on average is achieved, herewith the heating process time shift of ~ 20 s for test sample vs. calibration sample.

[0155] The results of the conducted studies prove the possibility of slowing down the emergency process of thermal runaway of lithium-ion batteries 2 by using a thermoreactive material containing a functional substance 8.

[0156] The achieved result of slowing down the rate of development of the emergency process, especially in combination with early detection of the onset of the thermal runaway, is significant in the light of high rate of development of the emergency process at the late stage.

[0157] It should also be noted that these results were obtained by modeling the thermal runaway process using simulators. Real thermal runaway of a lithium-ion battery occurs under conditions of consuming of the electrochemical energy accumulated in the battery cell and a decrease in heating power in the process of electrochemical thermal runaway. In the experiments carried out, the power was remained constant during the test. This allows us to declare that the effect of slowing down thermal runaway caused by the proposed use of thermoreactive material will be more significant and the time of catastrophic phase can be significantly delayed.

[0158] An additional result of the tests conducted is that the practical feasibility and possibility of achieving sufficient sensitivity of detection of the functional substance within the framework of the proposed technical solution have been proven, even based on the use of a cheap version of a non-specific mass-produced sensor.

INDUSTRIAL APPLICABILITY

[0159] The claimed invention meets the criterion of industrial applicability, since it can be manufactured using known technical means.

[0160] At the time of creation of the claimed technical solution, the problem of reducing the risks of severe consequences of fire of lithium-ion batteries is generally recognized as relevant. Moreover, the technical solution proposed in the present invention is applicable in the production and use of stationary or mobile lithium-ion electric energy storage systems used as primary or alternative power sources for a wide range of consumers from general power supply networks to mobile power sources for vehicles with the conversion of electrical energy into motion energy. All specific technical solutions applied in the present invention are practically implementable. In particular, all chemical compounds described in the technical solution are industrially produced and supplied to the market. The technology of microencapsulation of a functional substance and the

formation of thermoreactive materials based on it has been developed and has industrial application in a number of other areas of technology. Means for detecting functional substances in the form of sensors and detectors are widely used in neighboring fields of technology, and are also industrially produced and supplied to the market. Thus, the proposed technical solution has practical value and the possibility of industrial implementation.

[0161] While the invention has been described with reference to specific preferred embodiments, it is not limited to these embodiments. The invention may be modified or varied in many ways and such modifications and variations, as it would be obvious to those skilled in the art, are within the scope and spirit of the invention and are included within the scope of the following claims.

[0162] List of numerals

- 1 – energy storage system housing,
- 2 – battery cell,
- 3 – functional substance detector (gas detector),
- 4 – battery cell coating based on thermoreactive material,
- 5 – structural component made of thermoreactive material,
- 6 – thermoreactive material binder,
- 7 – microcapsule filled with functional substance in a liquid phase,
- 8 – functional substance in a liquid phase.
- 9 – functional substance in a gaseous phase,
- 10 – emergency heated battery cell,
- 11 – energy storage monitoring/management/control system,
- 12 – test chamber,
- 13 – test sample (simulator),
- 14 – heater,
- 15 – thermocouple,
- 16 – heating power control unit (power supply control unit),
- 17 – temperature sensor signal converter,
- 18 – gas detector signal converter
- 19 – data recording unit (data log unit),
- 20 – calibration sample (simulator).

CLAIMS

1. A lithium-ion energy storage system comprising
a plurality of lithium-ion battery cells mounted within a housing,
at least one functional structural component thermally linked to at least a part of
an outer surface of each lithium-ion battery cell and made of material comprising a
functional composite thermoreactive compound comprising microcapsules filled with a
functional substance in a liquid state, the functional substance comprising perfluoro(2-
methyl-3-pentanone) and a filler enhancing thermal conductivity of the material,

wherein the microcapsules are configured to break when heated to a specific
critical temperature in case of emergency heating of at least one lithium-ion battery cell
and to release the functional substance, which then gasifies, providing at least partial
cooling and/or fire suppression for the at least one lithium-ion battery cell, and

at least one gas detector configured to detect the functional substance in its
gaseous phase within the housing and to generate a signal indicating the occurrence of
emergency heating of the at least one lithium-ion battery cell.

2. The lithium-ion energy storage system according to claim 1, wherein the specific
critical temperature is in a range of 70-140°C.

3. The lithium-ion energy storage system according to claim 2, wherein the
capsules are made to start breaking at a temperature in the range of 70 - 80°C.

4. The lithium-ion energy storage system according to claim 1, wherein at least
one functional component made of the material comprising the microcapsules is
configured so that at least a portion of the microcapsules is thermally linked to at least a
part of the outer surface of each lithium-ion battery cell, ensuring heat transfer from each
lithium-ion battery cell to a portion of the microcapsules.

5. The lithium-ion energy storage system according to claim 1, wherein the
functional substance is perfluoro(2-methyl-3-pentanone) or a mixture of perfluoro(2-
methyl-3-pentanone) with at least one auxiliary halogenated organic chemical compound,
selected from hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons,
perfluoropolyethers, hydrofluoroethers, hydrofluoropolyethers, chlorofluorocarbons,
bromofluorocarbons, bromochlorofluorocarbons, iodofluorocarbons,

hydrobromofluorocarbons, hydrobromocarbons, or fluorinated ketones.

6. The lithium-ion energy storage system according to claim 1, wherein a volume of the functional substance in the microcapsules within the at least one functional component, when a portion of the microcapsules is heated to the predetermined critical temperature in case of emergency heating of at least one lithium-ion battery cell within the lithium-ion energy storage system and after release of the functional substance as a result of the destruction of the microcapsules shell, provides a volume of the functional substance in its gaseous phase sufficient for detection by the at least one gas detector.

7. The lithium-ion energy storage system according to claim 1, wherein the functional composite thermoreactive compound further comprises a cold-curing polymer binder configured to fix the microcapsules within the lithium-ion energy storage system.

8. The lithium-ion energy storage system according to claim 1, wherein the at least one functional structural component is configured as a coating of at least a part of each lithium-ion battery cell, wherein the coating comprises the microcapsules and a cold curing binder to attach the microcapsules to at least a part of the outer surface of each lithium-ion battery cell, as the battery cell structural component, to ensure that a sufficient portion of the microcapsules is thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

9. The lithium-ion energy storage system according to claim 1, wherein the at least one functional structural component is configured as at least one film or at least one insert, made of material including the functional composite thermoreactive compound, ensuring that sufficient portion of the microcapsules are thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

10. The lithium-ion energy storage system according to claim 1, wherein the at least one structural component is designed to fix lithium-ion battery cells within the lithium-ion energy storage system and is configured as a pouring compound made of the material filled with the microcapsules with functional substance, ensuring that the sufficient portion of the microcapsules are thermally linked to at least a part of the outer surface of each lithium-ion battery cell.

11. The lithium-ion energy storage system according to claim 1, wherein the material of the functional structural component comprises the filler enhancing thermal conductivity of the material by adding the filler in an amount of 30-70% of a total mass of the functional composite thermoreactive compound in the material content for at least one of the at least one functional structural component.

12. The lithium-ion energy storage system according to claim 1, where the at least one gas detector is connectable to an external control and alarm system.

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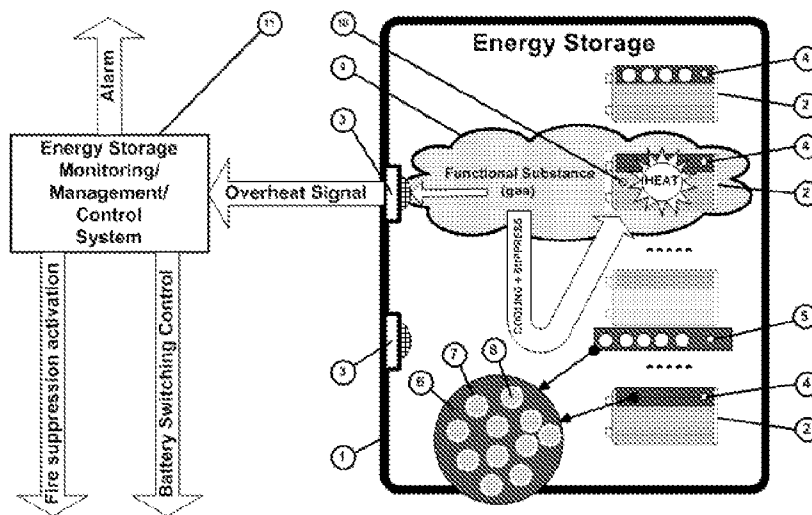


FIG. 1

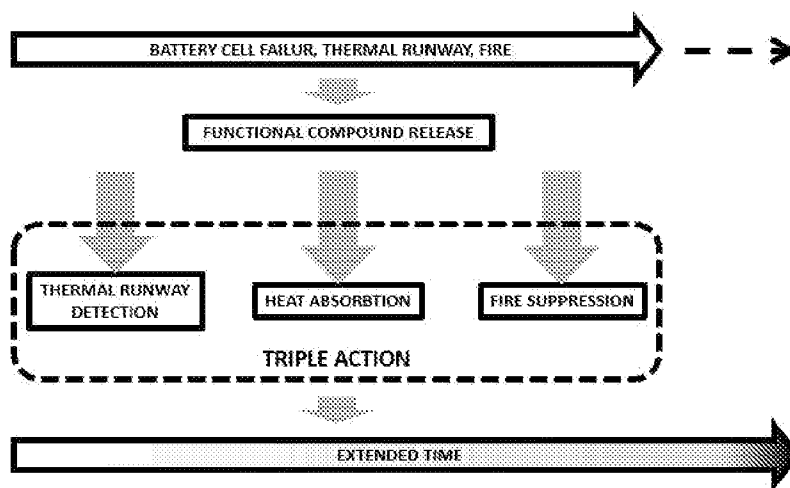


FIG. 2

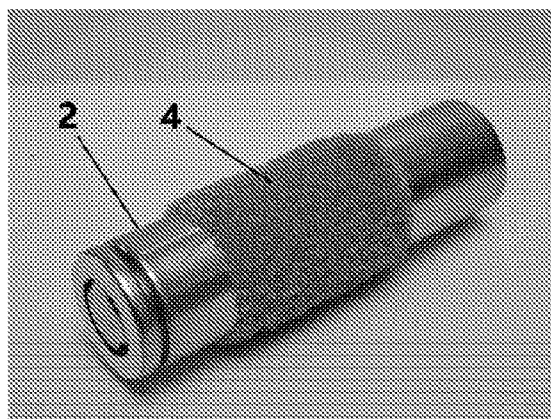


FIG.3

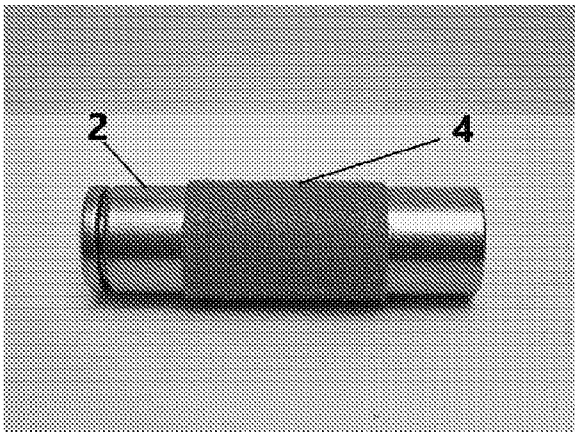


FIG. 4

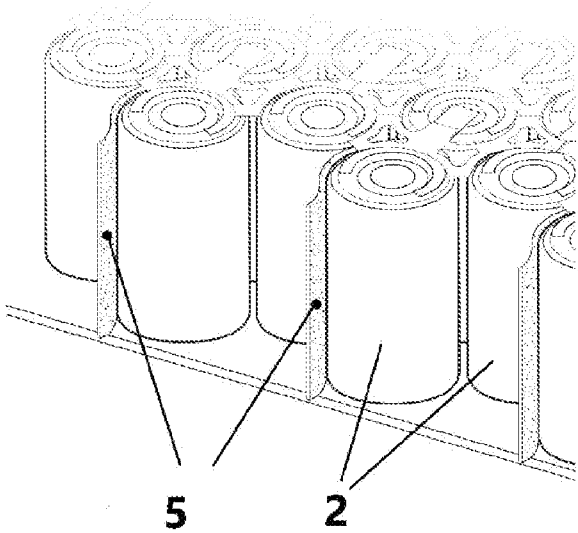


FIG. 5

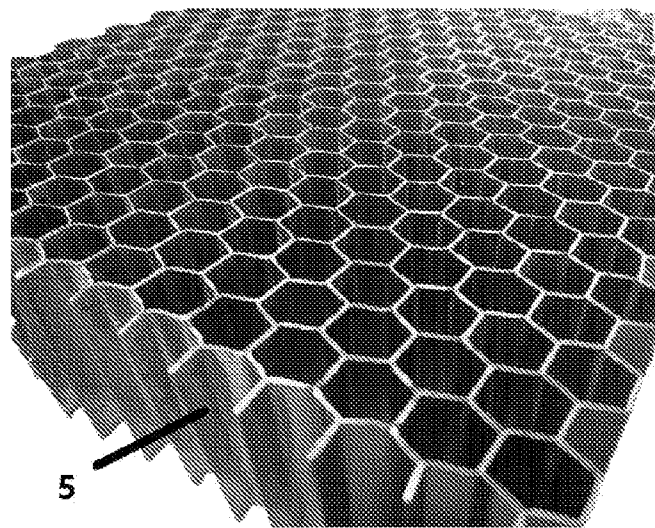


FIG. 6

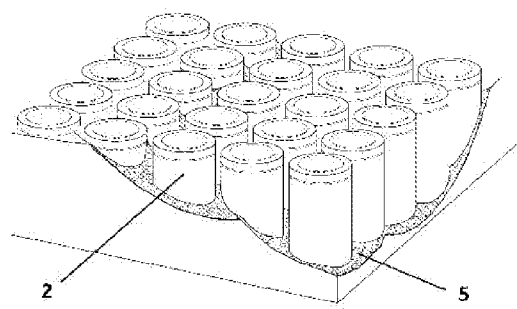


FIG. 7

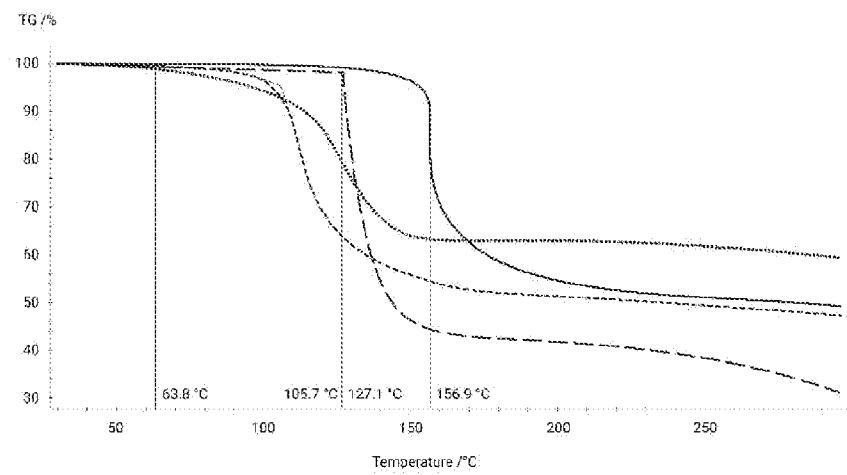


FIG. 8

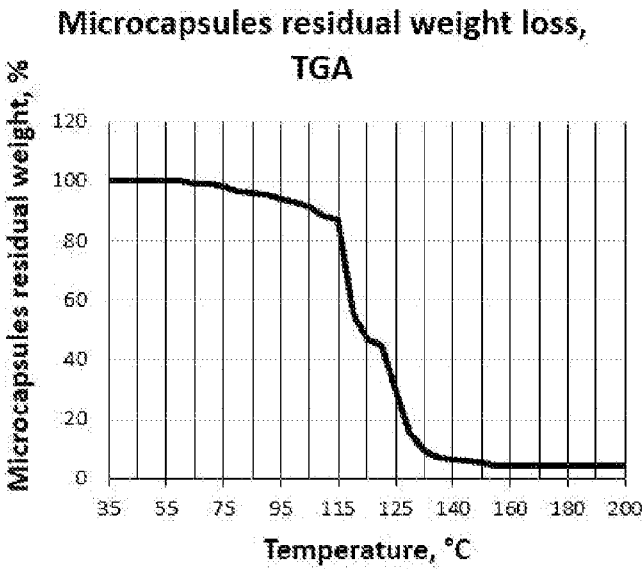


FIG. 9

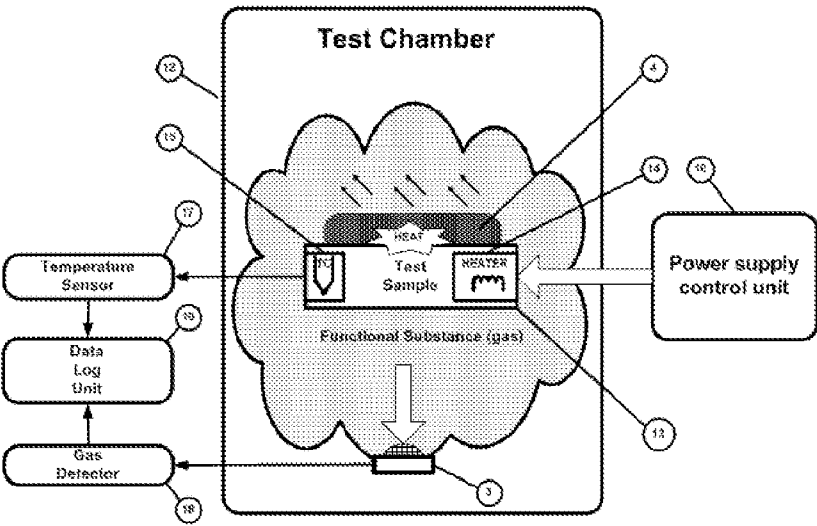


FIG. 10

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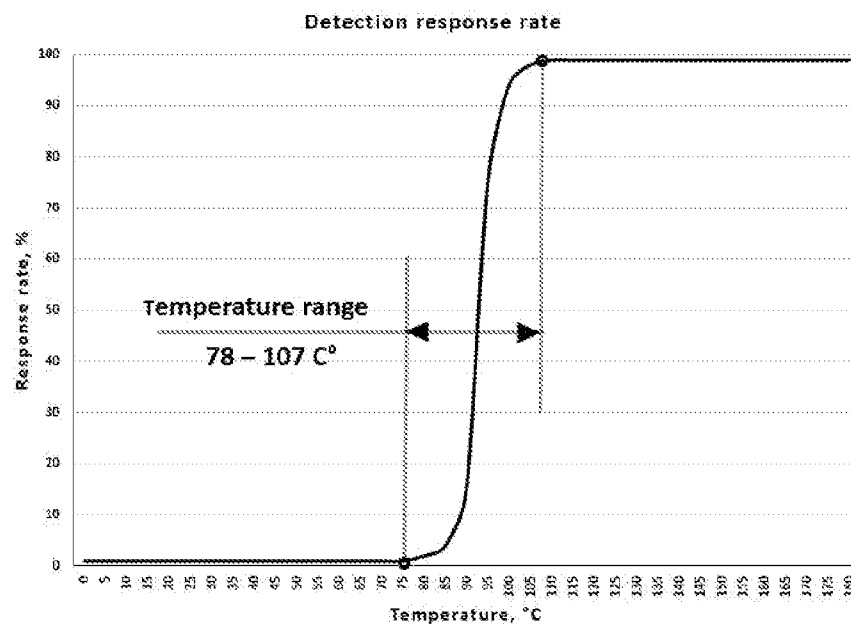


FIG. 11

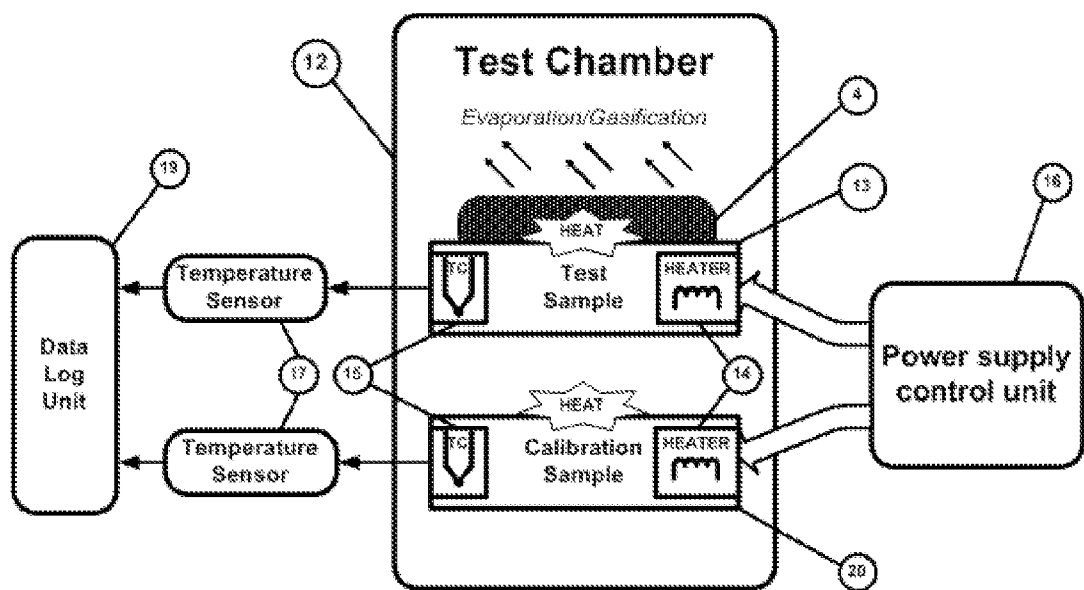


FIG. 12

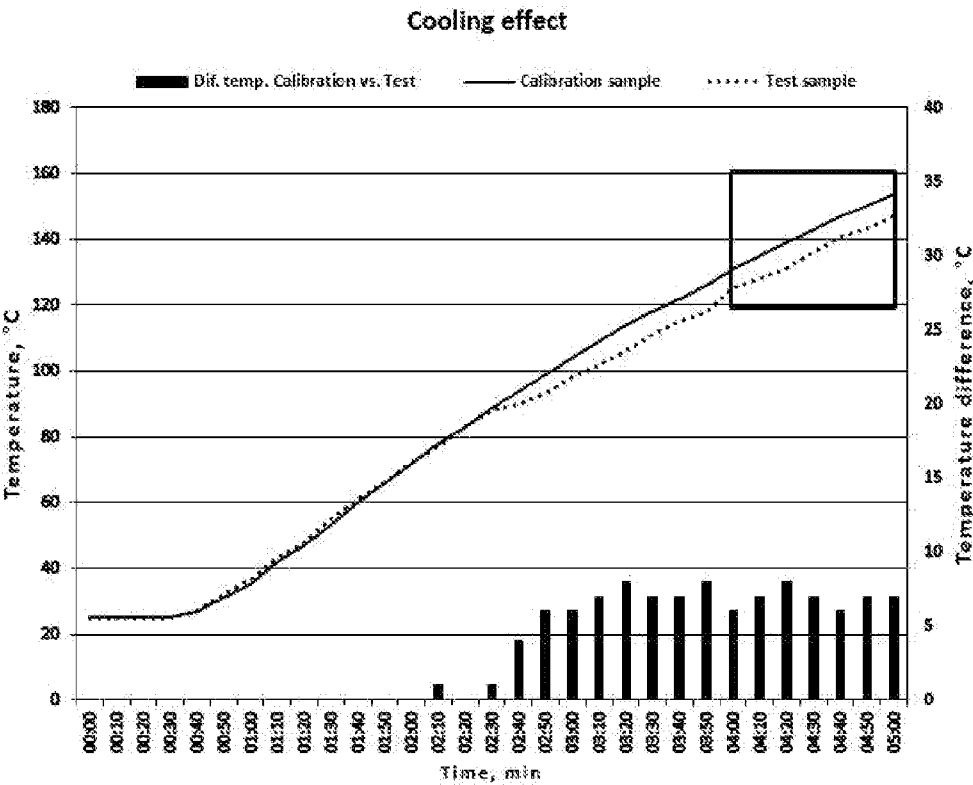


FIG. 13

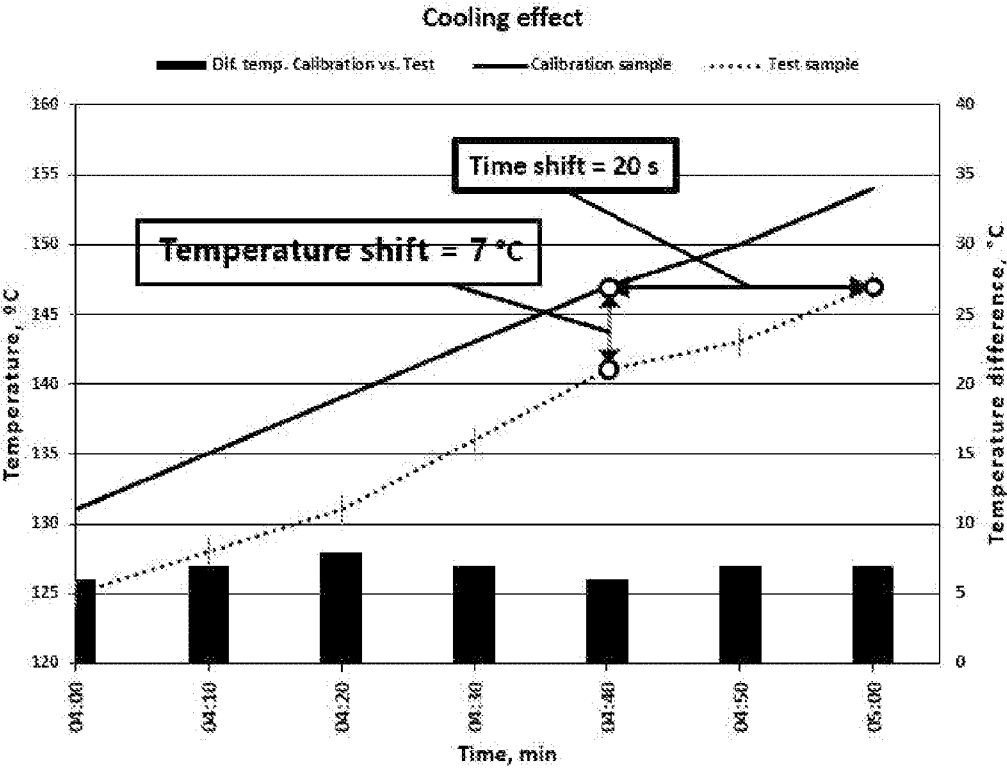


FIG. 14