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COMPREHENSIVE SOLUTIONS FOR AUTOMATIC FIRE SUPPRESSION OF ELECTRIC VEHICLE BATTERIES

The growing number of electric vehicles worldwide presents new challenges related to fire hazards. Spontaneous combustion of batteries may result from overheating, damage, or short circuits. This article aims to develop a comprehensive solution for an automatic fire suppression system for electric vehicle batteries. Considering the structural characteristics of a battery pack of an electric vehicle, one of the most effective ways to suppress a fire is by cooling the battery cells with water. Fire suppression efficiency can be improved by implementing design modifications to the battery housing, including the addition of water supply and drainage pipelines. This enables the development of an automatic fire suppression system that functions while the vehicle is parked or charging. In the event of a fire while an electric vehicle is in motion, the presence of pipelines will facilitate faster response by fire and rescue units.

To determine the key parameters of an automatic fire suppression system for electric vehicles, appropriate methods are proposed to assess the required amount of water for a specific vehicle model, the maximum water consumption for fire suppression, and the necessary pipeline diameters. The system is controlled by a PID controller, ensuring a rapid and appropriate response to combustion events in electric vehicle batteries while minimising the risk of uncontrolled fire spread. The scientific novelty of this study lies in the development of a methodological framework for enhancing fire suppression systems for electric vehicle batteries by establishing methods for determining the key parameters of an automatic fire suppression system. The practical significance of the obtained results lies in the formulation of design proposals for an automatic fire suppression system for an electric vehicle that manufacturers can implement in practice.

Keywords: *electric vehicle, battery, fire, fire hazards, automatic fire suppression system, extinguishing agent*

Problem statement. Statistical data on the fire hazards of electric vehicles in Ukraine and EU countries indicate that electric vehicles are less likely to catch fire than vehicles with internal combustion engines. However, the growing global popularity of electric vehicles introduces new fire safety challenges, particularly concerning battery fire hazards. Spontaneous combustion of batteries may result from overheating, damage, or short circuits. The ignition of electric vehicles in garages, underground, or enclosed parking areas with a high vehicle density poses significant risks. In the event of an electric vehicle fire, conventional fire suppression agents such as water and foam are generally ineffective and require a substantial amount of water to suppress fire. Automatic fire suppression systems present a promising solution as they can respond quickly and reduce the likelihood of uncontrolled fire spread.

Analysis of recent research and publications. The authors have analysed studies on the issues of fire protection of electric vehicles. Reference [1] analyses the factors influencing the fire hazards of electric vehicles, including design, operational, and maintenance factors. Design factors encompass battery type, capacity, the presence of safety and control systems, and mechanical damage protection. Operational factors include vehicle service life and charge/discharge management. Maintenance factors involve adherence to maintenance regulations and the use of standard chargers. Other researchers have explored the development of the concept of a system based on a vanadium-air battery, which is used to ensure the charge and fire safety of electric vehicles by reducing oxygen in sealed compartments [2]. Research in [3] evaluates evacuation strategies for pedestrians during an electric vehicle fire. Based on the results, it is possible to assess a safe distance to neighbouring vehicles and the total value of pedestrians affected by thermal radiation from an electric vehicle fire under the influence of environmental factors. The proposed model can optimise the design of roadside parking areas and inform emergency planning for pedestrians during an electric vehicle fire. Another study models an electric vehicle fire in a closed parking structure using a Tesla Model S to determine the minimum required fire protection distances [4].

Several scientific works focus on fire and rescue response procedures for electric vehicle fires. Guidelines have been developed for the actions of fire and rescue units at the scene of an incident to ensure safe working conditions and efficient emergency response, including strategies for deploying fire and rescue personnel based on fire origin points [5]. Reference [6] outlines an algorithm of actions for fire suppression managers upon arrival at the scene of an emergency involving the ignition of an electric vehicle. Compliance by the fire suppression manager with the above algorithm of actions will minimise the risks to the personnel of the operational and rescue unit and facilitate faster fire suppression.

Studies on fire extinguishing agents for batteries highlight various approaches. Reference [7] confirms the effectiveness of carbon dioxide in extinguishing lithium-ion battery fires. Potassium aluminium carbonate-based fire suppression powders with improved thermal resistance have also been developed for lithium-ion batteries [8]. Additionally, finely atomised water has been proven to effectively absorb heat and cool lithium-ion batteries during combustion [9, 10]. However, these studies do not sufficiently address automatic fire suppression systems for electric vehicles.

Statement of purpose of the article. This article aims to develop a comprehensive solution for an automatic fire suppression system for electric vehicle batteries.

To achieve this, the following objectives must be fulfilled:

– investigate the characteristics of electric vehicle fires;

– determine the key parameters of an automatic fire suppression system for electric vehicles;

– propose design solutions for the automatic fire suppression system of electric vehicles.

Presentation of basic material of the research. Electric vehicle batteries typically consist of individual cells arranged in series and parallel connections fig. 1a, b. These cells are enclosed within a sealed battery housing fig. 2a, b, making conventional fire suppression methods, such as external application of extinguishing agents via fire hoses, ineffective. Effective fire suppression requires direct cooling of battery cells.

a *b*

Figure 1 – Contents of the battery pack: *a* – Nissan Leaf; *b* – Tesla car module

a *b*

Figure 2 – Battery pack of an electric vehicle in a housing: *a* – Nissan Leaf 24 kWh; *b* – Tesla 100 kWh

A promising approach involves immersing the entire electric vehicle in a water tank [5]. However, this method has significant drawbacks, including prolonged fire spread before suppression begins, leading to severe vehicle damage.

Instead, this study proposes a targeted fire suppression method in which extinguishing agents are supplied directly into the battery housing to effectively suppress fires and prevent further development of fire hazard. This approach requires modifications to the battery design, incorporating pipelines with connection heads for water supply and drainage, as well as a removable bottom cover to facilitate complete water evacuation after suppression fig. 3.

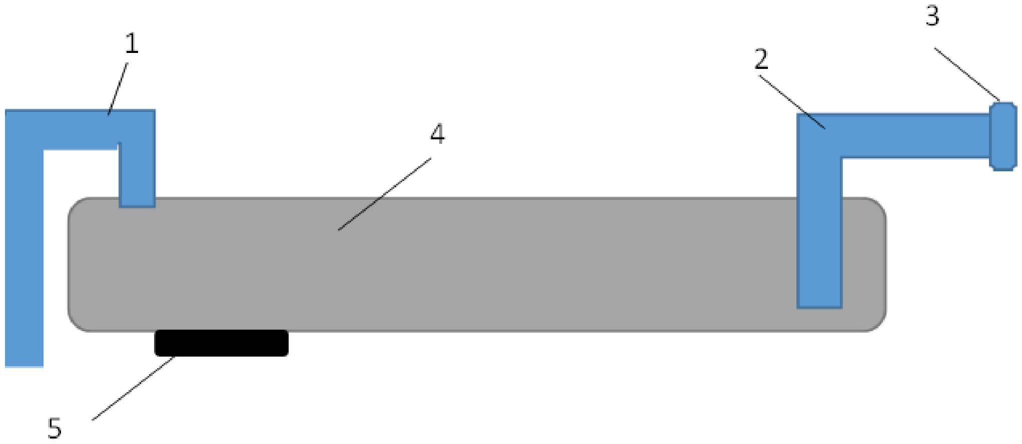

Figure 3 – Schematic of a battery pack of an electric vehicle with fire suppression pipelines: 1 – water drainage pipeline, 2 – water supply pipeline, 3 – connecting head, 4 – battery housing, 5 – extinguishing agent drain cover

Water can be supplied to the battery internal space either automatically or via a fire truck.

Automatic fire suppression is feasible when the vehicle is parked or charging. To this end, a special automatic fire suppression system consisting of integrated vehicle components and external elements at charging stations is proposed.

Fire detectors installed in the battery housing identify fire hazards based on temperature increases, smoke, or combustion-related gas emissions. Given that this method involves water filling the battery housing, detectors must have an enclosure rating of at least IP67. This design allows the electrical equipment to be completely in water, but at a specified pressure.

The supply of fire extinguishing agent must be regulated to ensure its efficient use. In case of high-intensive fires, water must be supplied at the maximum flow rate, while low-intensity fires necessitate minimal flow, with automatic shutoff when no heat is detected in the battery housing.

This is achieved via an extinguishing agent pump with variable speed control or an adjustable valve (gate valve).

The decision to supply or stop extinguishing agents must be automated. An electronic control system must be provided that will process data from the vehicle sensors and control the operation of the automatic system components. Integration with other safety systems, such as fire alarms, enables early detection and alerts for fire and rescue units.

Determining the main parameters of the automatic fire suppression system of an electric vehicle. Determining the amount of water required for the effective operation of the fire suppression system in a battery pack of an electric vehicle is a task that requires some calculations and considerations. The main factors to consider are battery capacity, type of battery cells, free volume of the battery housing, system efficiency, and fire intensity.

The battery capacity determines the amount of possible heat generated during battery combustion, so this value must be taken into account when determining the amount of water required for fire suppression.

The type of battery cells will determine the amount of heat they will generate during combustion. Also, distinct types of battery cells differ in size and shape, which in turn will affect the intensity of the fire. Therefore, the type of battery cells must be taken into account when assessing the rate of heat generation and the potential for heat release.

The free volume of the battery housing is the volume of its internal space without taking into account the volume of battery cells, wires, fasteners and other battery components. This value is necessary to determine the minimum amount of water required to completely fill the internal volume of the battery.

The system efficiency is defined as the ratio between the amount of water that cools the burning cells and the amount of water consumed by the automatic fire suppression system.

The fire intensity determines the water consumption for fire suppression at any given time. It can be determined by measuring the temperature difference between the water in the inlet and outlet pipelines.

The pressure and volume of water supplied by the system play a significant role. They must be sufficient to ensure cooling. Depending on how quickly the fire develops, more or less water may be needed to suppress it effectively.

Calculating the exact amount of water required will require appropriate calculations and testing of the system in real-world conditions. Subsequently, engineering calculations can take into account all these factors to determine the optimal system parameters for a particular type of electric vehicle and its battery.

The methods for determining the main parameters of the automatic fire suppression system of electric vehicles involve the following steps:

Stage 1. Calculating the amount of heat released during the combustion of a 100% charged electric vehicle battery.

Stage 2. Determining the total amount of water required to suppress fire in a battery pack of an electric vehicle.

Stage 3. Determining the maximum water consumption for suppression a fire.

Stage 4. Determining the parameters of the automatic fire suppression system — pipeline diameters, required flow rate and operating pressure of the pumps.

Stage 5. Determining the relationship between the temperature difference between the inlet and outlet pipelines and the required coolant flow rate, to be used in the algorithm of the automatic fire suppression system.

The calculation of the amount of heat that can be released during the combustion of a battery pack of an electric vehicle can be performed knowing the number of battery cells and the amount of heat generated during the combustion of one battery:

$$W_{max} = W_{ел} \cdot n, \tag{1}$$

where W_{max} is the maximum possible amount of heat during the complete combustion of all battery cells in the battery pack;

$W_{ел}$ is the amount of heat released during the combustion of one battery cell;

n is the number of battery cells.

If the exact number of battery cells is unknown, approximate calculations can be made based on the type of battery cells and the total capacity of the battery pack:

$$W_{max} = \frac{C \cdot H_c}{E}, \tag{2}$$

where E is the specific energy for a given type of battery cell, kWh/kg;

C is the total capacity of the battery pack, kWh;

H_c is the calorific value, J/kg.

Based on the obtained values of the maximum amount of heat, let us determine the required amount of water for fire suppression:

$$V_{max} = \rho_{\text{в.р.}} \frac{W_{max}}{c(T_2 - T_1)} K_з, \tag{3}$$

where V_{max} is the volume of water for fire suppression;

$\rho_{\text{в.р.}}$ is the density of water;

c is the heat capacity of water;

T_1 is the initial water temperature;

T_2 is the permissible water temperature at the outlet of the battery housing;

$K_з$ is the safety factor.

The initial temperature in these methods can be accepted as the ambient temperature, i.e. 20˚C. The permissible water temperature at the outlet of the battery housing varies based on the condition of preventing dangerous overheating of the battery cells, and can be selected as the permissible temperature for polyvinyl chloride insulation — 70˚C. When designing fire suppression systems, it is customary to provide for a 100% reserve of extinguishing agent, so the safety factor can be 2.

The next stage involves establishing the main permissible parameters of the automatic fire suppression system: pipeline diameter and required pump flow rate.

The diameter of the pipeline is selected based on the condition:

$$d \geq \sqrt{\frac{4Q_{max} \cdot 10^{-3}}{\pi \cdot \vartheta_{max}}}, \tag{4}$$

where d is the diameter of the pipeline;

ϑ_{max} is the permissible velocity of the extinguishing agent;

Q_{max} is the maximum design water flow rate.

The permissible velocity of the extinguishing agent ϑ_{max} for fire suppression systems is usually no more than 10 m/s.

The maximum design water flow rate is Q_{max}:

$$Q_{max} = \frac{V_{max}}{t_{\text{В.Г.}}}, \tag{5}$$

where $t_{\text{В.Г.}}$ is the free burning time of the electric vehicle battery.

The free burning time can be determined approximately based on the simplifications that the fire is formed in the centre of the battery, the battery cell in the row next to this cell ignites after heating and the heat generation stops after the outermost cell burns out. The following dependence can then be used:

$$t_{\text{В.Г.}} = \frac{N_{\text{р.е.}} \cdot t_{\text{н.е.}}}{2} + t_{\text{г.е.}}, \tag{6}$$

where $N_{\text{р.е.}}$ is the number of rows of battery cells;
$t_{\text{н.е.}}$ is the time for the battery cell to heat up before ignition;
$t_{\text{г.е.}}$ is the duration of burning of one battery cell.

At the last stage of the methodology, the dependence between the temperature difference between the inlet and outlet pipelines is determined. And with the help of a PID controller, the required coolant flow rate is determined for this difference.

Rationale for the design of an automatic fire suppression system for electric vehicles. The automatic fire suppression system for a battery pack of an electric vehicle is designed to respond safely and effectively to a fire during charging. It has two parts — those built into the electric vehicle and those located at the charging station.

The design of the automatic fire suppression system of electric vehicles includes the following elements built into the electric vehicle:

– a pipeline with a connecting head: a special tube connected to the battery housing to supply water in the event of a fire;

– fire detectors: located inside the battery, they are activated in the event of a fire, alerting about the problem;

– outlet pipeline: supplies water to the internal space of the battery housing to cool the cells;

– temperature sensors: measure the temperature of the water at the inlet and outlet of the battery housing to adjust the flow rate depending on the intensity of the fire.

Elements on the charging station:

– a tank or pipelines from a centralised water supply system: provide the system with water for fire suppression.

– control system detects the threat, activates suppression, and coordinates the work of all elements, has a built-in PID controller that adjusts the water flow rate depending on the temperature difference for effective fire suppression.

– pump with water flow control creates the required pressure for the water supply based on the temperature data.

– connection pipelines: dedicated pipelines for connecting to the electric vehicle components.

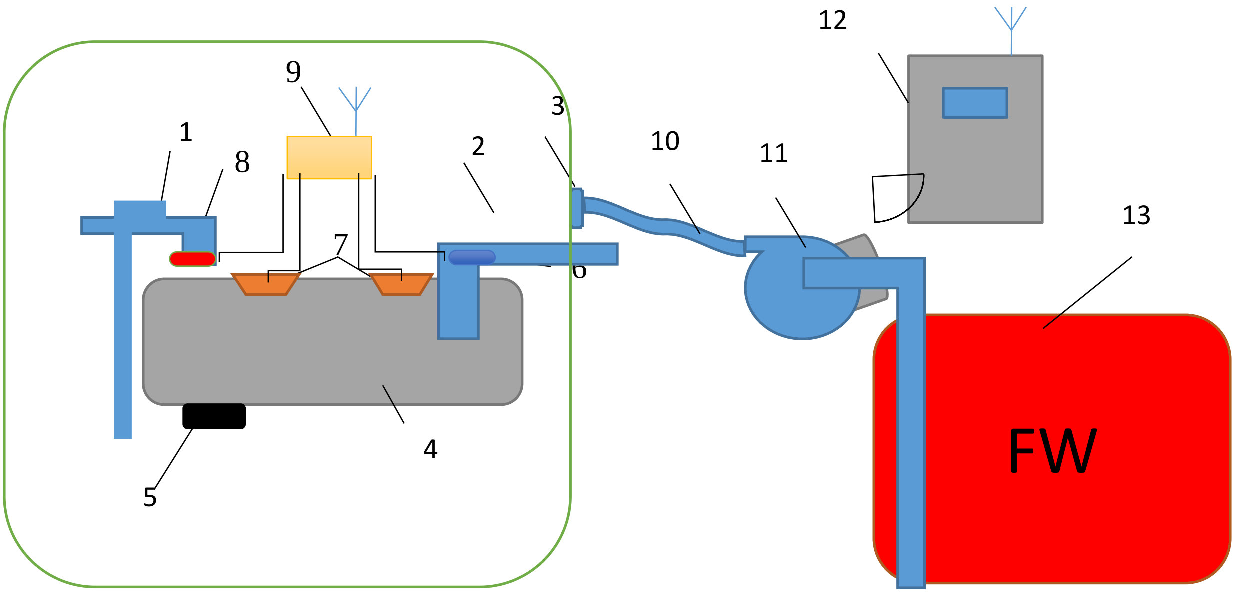

Figure 4 – Schematic diagram of an automatic fire suppression system for a battery pack of an electric vehicle: 1 – water drainage pipeline, 2 – water supply pipeline, 3 – connecting head, 4 – battery housing, 5 – extinguishing agent drain cover, 6 – temperature sensor at the inlet to the battery housing, 7 – fire detectors, 8 – water temperature sensor at the outlet of the housing, 9 – wireless information transmission unit, 10 – flexible pipeline, 11 – fire pump, 12 – control panel, 13 – fire tank

PID controllers are used to control the flow of water depending on the temperature difference between the inlet and outlet temperatures and are widely used to control various processes. PID controllers form proportional, integral, and differential controllers combined in such a way that the result of operation is a control signal. This system is designed to respond reliably to a fire that may occur during the charging of a battery pack of an electric vehicle, ensuring safety and protection against the undesirable consequences of an emergency.

Conclusions. Considering the structural characteristics of a battery pack of an electric vehicle, one of the most effective ways to suppress a fire is by cooling the battery cells with water. However, the sealed nature of battery housings complicates this process. Fire suppression efficiency can be improved by modifying battery housing designs to incorporate water supply and drainage pipelines. These modifications enable the development of an automatic fire suppression system that operates while the vehicle is parked or charging. In the event of a fire while an electric vehicle is in motion, the presence of pipelines will facilitate faster response by fire and rescue units.

To determine the key parameters of an automatic fire suppression system for electric vehicles, appropriate methods are proposed to assess the required amount of water for a specific vehicle model, the maximum water consumption for fire suppression, and the necessary pipeline diameters. The system is controlled by a PID controller, ensuring a rapid and appropriate response to combustion events in electric vehicle batteries while minimising the risk of uncontrolled fire spread.

The scientific novelty lies in the development of the scientific basis for improving the fire suppression systems of a battery pack of an electric vehicle on the basis of the proposed methods for determining the main parameters of the automatic fire suppression system of an electric vehicle.

The practical significance of the obtained results lies in the formulation of design proposals for an automatic fire suppression system for an electric vehicle that manufacturers can implement in practice.

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КОМПЛЕКСНІ РІШЕННЯ ЩОДО АВТОМАТИЧНОГО ГАСІННЯ ПОЖЕЖІ АКУМУЛЯТОРНОЇ БАТАРЕЇ ЕЛЕКТРОМОБІЛЯ

Зростання кількості електромобілів в усьому світі супроводжується новими викликами в питаннях пожежної небезпеки. Самозаймання акумуляторних батарей може виникати через процеси перегріву, пошкодження, короткого замикання. Метою статті є розробка комплексного рішення щодо створення системи автоматичного гасіння акумуляторної батареї електромобиля. Враховуючи особливості будови акумуляторної батареї електромобіля одним із найефективніших способів її гасіння є охолодження елементів живлення водою. Підвищити ефективність гасіння можна шляхом внесення в конструкцію корпусу батареї ряду конструктивних змін, зокрема додавання трубопроводів для подачі та відведення води. Це дозволяє побудувати автоматичну систему пожежогасіння, яка працюватиме під час стоянки та заряджання автомобіля. У разі виникнення пожежі під час руху електромобіля наявність трубопроводів дозволить пришвидшити гасіння пожеж пожежно-рятувальним підрозділами.

Для визначення основних параметрів системи автоматичного пожежогасіння електромобіля запропонована відповідна методика, яка дозволяє визначити: необхідну кількість води для конкретної марки електромобіля, максимальну витрату води на гасіння, діаметри трубопроводів. Автоматична система пожежогасіння здійснює керування за допомогою ПІД-регулятора, що дозволяє забезпечити оперативну та адекватну реакцію на виникнення горіння в акумуляторній батареї електромобіля та зменшує ймовірність неконтрольованого поширення горіння.

Ключові слова: *електромобіль, акумуляторна батарея, пожежа, небезпечні чинники пожежі, автоматична система пожежогасіння, вогнегасна речовина*.