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USE OF VARIOUS FIRE EXTINGUISHING AGENTS IN HANDLING ELECTRIC VEHICLE FIRES

Supri (1) , Surya Tri Sapurta(2) , Wildan Nugraha (3)
[1,2,] Indonesian Aviation Polytechnic Curug, [3] Palembang Aviation Polytechnic
email: [1] supri.supri@ppicurug.ac.id, [2] suryatri@ppicurug.ac.id,
[3] wildan.nugraha@poltekbangplg.ac.id
korespondensi: [1] supri.supri@ppicurug.ac.id

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Abstract: Electric vehicles (EVs) have become a popular choice for environmentally friendly transportation, supported by various government policies in Indonesia. However, the increase in EVs presents new safety challenges, particularly regarding electric vehicle fires. Handling these fires requires different strategies compared to conventional vehicle fires, with the use of fire extinguishing agents believed to significantly impact these challenges. This review follows PRISMA-ScR guidelines within a PEO framework. Searches were conducted through Science Direct and Google Scholar from 2014 to 2024, screening articles with Mendeley and Covidence. Out of 230 articles, 9 relevant studies were selected. The review identifies three main themes: types of extinguishing agents, methods of use, and trial outcomes. The study finds that the best method for managing electric vehicle fires is using a combination of extinguishing agents, proving to be the most effective choice for rapid extinguishment, temperature control, and reducing the risk of fire reignition.

Keywords: *Electric vehicles, vehicle fires, extinguishing*

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Introduction

Electric Vehicles (EVs) have become a favored choice as a cleaner and more environmentally friendly transportation alternative. In efforts to address climate change, governments and automotive manufacturers worldwide have taken proactive steps to reduce carbon emissions by promoting the use of electric vehicles. Through investment strategies and policies specifically designed to support the adoption of electric vehicles, both parties have contributed to accelerating the transition towards sustainable transportation solutions. These policies have successfully driven the increase in electric vehicle production, making them the primary choice for the future of the transportation sector (International Energy Agency (IEA), 2022)

In Indonesia, Presidential Regulation Number 55 of 2019 marks progress related to electric vehicles with the main goal of accelerating the adoption of Battery Electric Vehicles (BEVs) in land transportation. The government has provided support through policies such as the elimination of the Luxury Goods Sales Tax (PPnBM) and special rates for electric charging. These measures, along with plans to phase out the sale of conventional motor vehicles by 2040 for two-wheelers and 2050 for four-wheelers, demonstrate the government's commitment to supporting the transition to electric vehicles (Saputra & Andajani, 2023).

However, the increasing number of electric vehicles on the road also brings new challenges, particularly related to safety. The use of these vehicles poses different safety challenges compared to conventional motor vehicles. Nevertheless, research on electric vehicle safety, especially those focusing on real-world accident data analysis, remains limited globally. This limitation poses challenges in developing and implementing effective mitigation strategies against the risks of electric vehicle fires (Liu et al., 2022).

Electric vehicle fires often occur due to overheating or improper use, whether the vehicle is parked or in operation, and can happen during battery charging, normal use, or after involvement in an accident. Overheating of lithium-ion batteries, in particular, makes electric vehicles more prone to fires compared to Internal Combustion Engine Vehicles (ICEVs) (Peiyi Sun dkk., 2022).

Address this risk, lithium-ion batteries are equipped with safety valves designed to release gas during thermal runaway. However, these safety systems cannot guarantee full protection because the released gas is highly flammable and can be triggered by external factors such as flames or electrical sparks. If gas production exceeds the valve's capacity, it can potentially cause the battery to explode (Scala et al., 2022).

The use of fire extinguishing agents in handling electric vehicle fires is a crucial effort in controlling and extinguishing fires. A study conducted by (Zhao et al., 2024) found that fire blankets are quite effective in extinguishing flames and reducing temperatures inside the vehicle, especially when the fire has just started. However, fire blankets are less effective in stopping the thermal runaway reaction in batteries. On the other hand, water mist sprays and compressed air foam have proven to be more efficient. Water mist sprays can quickly reduce temperatures and extinguish fires, while compressed air foam can extinguish fires very rapidly.

Furthermore, a literature review by (Supri, 2024) on innovative strategies for handling electric vehicle fires identified that six studies utilized water-based extinguishing agents, either alone or in combination with other agents such as CO2, $C_6F_{12}O$, liquid nitrogen, and foam, demonstrating their effectiveness in extinguishing fires in electric vehicles. However, this literature review did not provide a comprehensive understanding of the use of various extinguishing agents in handling electric vehicle fires.

This research provides a deeper understanding of handling electric vehicle fires with a different and more comprehensive approach compared to previous literature reviews by (Supri, 2024). In this study, a critical assessment of several articles related to this theme was conducted, which were then mapped based on the type of extinguishing agent, the method of using the extinguishing agent, as well as the effectiveness and efficiency of each extinguishing agent. Therefore, this research is expected to provide a stronger foundation for the development of policy implementation of best practices and guide further research for technological innovation in handling electric vehicle fires. This research is important to fill the gaps in the current literature and provide practical guidance that can be applied in the field.

Objectives

The objective of this scoping review is to map research findings on the use of various extinguishing agents in handling electric vehicle fires, and to identify the types of extinguishing agents, methods of use, as well as the effectiveness and efficiency of each extinguishing agent.

The PEO framework is used in this scoping review. This framework helps researchers formulate research questions by determining the Population to be studied, the Exposure, and the Outcome. In this scoping review, the population consists of firefighters, the exposure is to electric vehicle fires, and the expected outcome is the handling of electric vehicle fires.

Methods

A scoping review is a research methodology designed to gather and analyze literature related to a specific topic or concept. This method aims to gain a broad understanding of the types of evidence available and their contributions to existing knowledge, as well as to identify potential directions for future research (Tricco et al., 2018). This study applies the PRISMA-ScR protocol formulated by (Tricco et al., 2018).This protocol consists of twenty-two criteria for assessment and twenty-two key points for reporting. However, the researchers did not conduct a registration process for this study. The eligibility criteria related to inclusion and exclusion are shown in Table 1.

Table 1. Inclusion and Exclusion Criteria

Components	Discussion
Inclusion Criteria	1. Articles relevant to the theme of handling electric vehicle fires 2. Articles in all languages 3. Articles published between 2014 and 2024 4. Full-text articles
Exclusion Criteria	1. Review articles, opinions, and brief reports

Researchers identified relevant articles through one database, ScienceDirect, and one search engine, Google Scholar. The last search was conducted on February 26, 2024. For this study, the keywords chosen for the literature search process were “electric vehicle accidents” OR “electric vehicle fires” AND “fire incidents” OR “fire management” OR “thermal runaway”. After entering the keywords, the search was then filtered to include all languages and primary research from 2014 to 2024. In the evidence source selection stage, researchers used Mendeley as a tool to manage references, with functions such as detecting duplicate articles, accessing abstracts, and reviewing full texts. After selecting the articles, researchers compiled summaries based on the characteristics of the literature studies, providing accurate information. Through comparison tables, researchers compared information on electric vehicle fire handling in developed and developing countries. The results of this literature review were then described after data comparison was conducted (Tricco et al., 2018). The Prisma flow diagram is presented as shown in Figure 1.

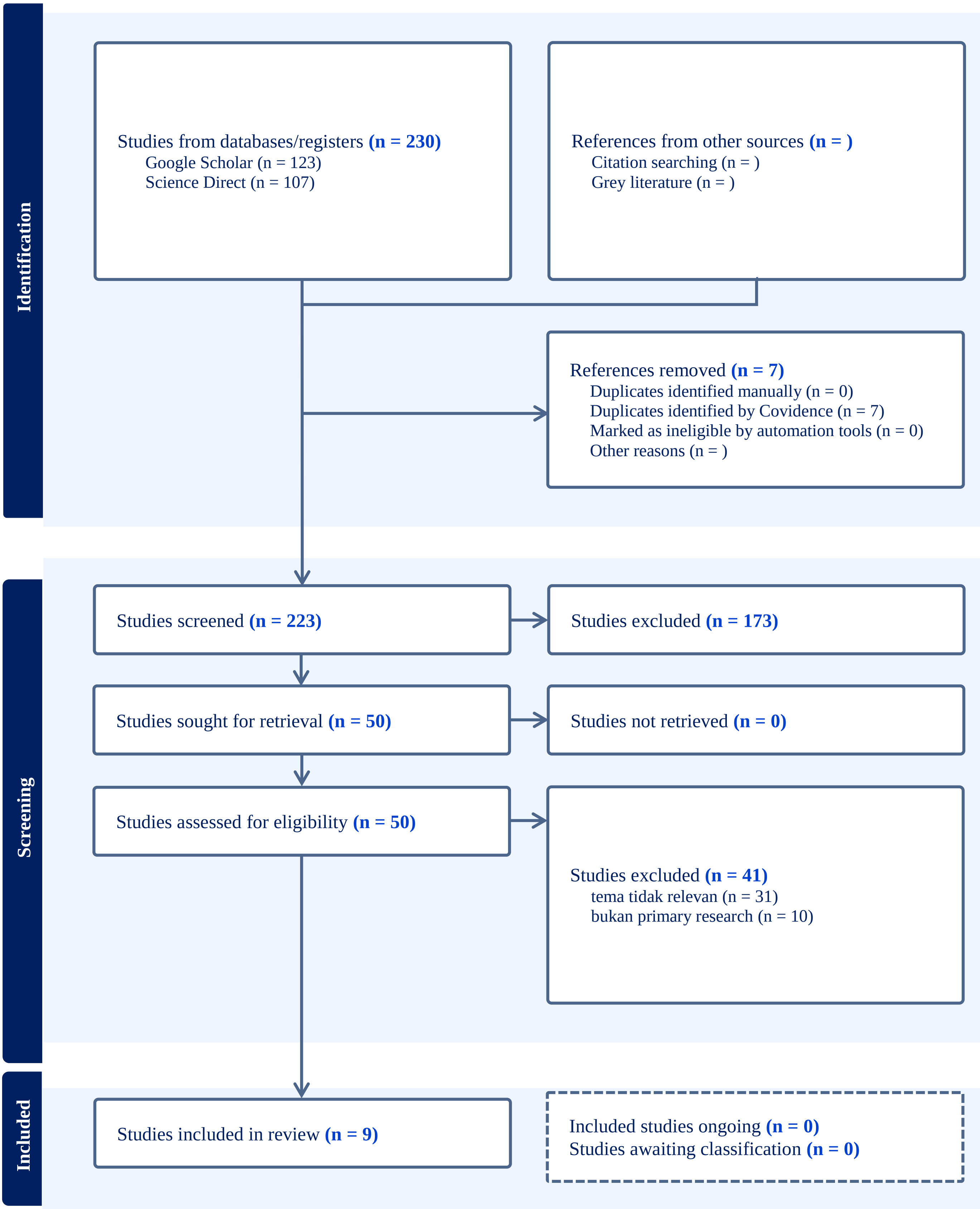

Figure 1. PRISMA-ScR Flow Diagram (Tricco et al., 2018)

Data Items

Researchers identified key points in the scoping review on handling electric vehicle fires, such as the use of various extinguishing agents, methods of application, and experimental results.

Critical Assessment of Evidence Sources

Researchers evaluated the quality and reliability of the sources by considering methodology, subject participation, measurements, constraints, potential bias, statistical analysis, alignment with research questions, and publication age. The Critical Appraisal tools used were from the Joanna Briggs Institute (JBI) (Porritt et al., 2014).

Based on the assessment results, all articles coded (A1 to A9) used experimental research designs with a consistent measurement value of 9. The critical appraisal results varied, with the highest score of 8 achieved by articles A5 and A6. Articles A1, A2, A3, and A7 each received a score of 5, while articles A4, A8, and A9 each scored 6. This assessment highlights the differences in quality and reliability of the sources based on various evaluated aspects.

Characteristics of Evidence Sources

The specific characteristics of the nine selected articles include identification details such as title, author(s), publication year, country of origin, research objectives, applied research methods, data collection procedures, sample size, and main findings. Data charting is presented in Table 2.

Results Synthesis

During the search process for articles related to the scope review on handling electric vehicle accidents, 9,600 articles were found from one database and Google Scholar, and 8,925 from Science Direct. After importing into Mendeley for reference management, the initial screening left 230 relevant articles. From this number, Prisma ScR identified 7 duplicates, leaving 223 articles for further screening. A total of 173 articles were found to be irrelevant and eliminated, while 50 articles were processed further for full-text evaluation. Finally, after screening based on inclusion criteria, only 9 articles met the eligibility requirements. Several themes were discussed in the Scoping Review conducted by the researchers. Based on the review of the nine articles in line with the objectives of the scoping review, several themes encompassing multiple sub-themes were identified. The theme mapping is presented in Table 3.

Table 3. Theme Mapping

Theme	Sub theme	Article
Group of Extinguishing Agents	Solid group	A1, A3
	Liquid group	A2, A3, A5, A6, A7
	Gas group	A2, A9
	Foam group	A1,A8
	Chemical group	A8
Methods of Use	Single Agent Use	A4,A5,A6,A7,A9
	Combination Agent Use	A1,A2,A3,A8
Experimental Results	Temperature Reduction	A1,A2,A3,A4,A5,A6,A7,A8
	Fire Extinguishing	A1,A2,A7,A8

Table 2. Data Charting

NO	Judul /Penulis/ Tahun	Negara	Tujuan	Jenis penelitian	Pengumpulan data	Ukuran Peserta/Sampel	Hasil
A1	Full-scale experimental study of the characteristics of electric vehicle fires process and response measures (Zhao, Hu, Meng, Mi, Wang, & Wang, 2024)	China	Investigating Response Strategies to Electric Vehicle (EV) Fires Caused by Thermal Runaway (TR) of Lithium-Ion Batteries and Fire Spread Patterns in Evs	Experimental	Measurement of internal and external temperatures of the vehicle and estimation of the length of fire jet flow using image processing	One fully functional electric vehicle	Fire blankets, water mist sprays, and compressed air foam were effective in extinguishing fires in the early stages, with compressed air foam providing the highest average cooling rate.
A2	Experimental study on the synergistic effect of gas extinguishing agents and water mist on suppressing lithium-ion battery fires (Zhang et al., 2020)	China	Investigating the Synergistic Effects Between Gas Extinguishing Agents and Water Mist in Extinguishing Lithium-Ion Battery Fires	The study involved the use of a large-scale 243 Ah battery with $LiFePO_4$ as the cathode	Measurement of cell parameters to evaluate extinguishing effects, such as extinguishing time, maximum temperature, mass loss, and heat release rate	The testing included six cases with different experimental conditions	The synergistic extinguishing method was more effective than using a single agent, with $C_6F_{12}O$ and the combination of $C_6F_{12}O$ with water mist demonstrating the best extinguishing and cooling effects.
A3	Full-scale Fire Suppression Tests to Analyze the Effectiveness of Existing Lithium-ion Battery Fire Response Procedures for Electric Vehicle Fires (Lim et al., 2021)	Korea Selatan	Evaluating response procedures for lithium-ion battery fires in eco-friendly vehicles using various extinguishing agents.	Experimental	Data were collected through direct observation of experiments with extinguishing agents, fire blankets, and temperature measurements.	Experiments were conducted on lithium-ion batteries with specific parameters, including capacity, voltage, energy, weight, and configuration of cells and modules.	No significant differences in temperature reduction effectiveness among extinguishing agents; direct cooling methods were more effective for damaged battery packs.
A4	Experimental investigation on the cooling and suppression effects of liquid nitrogen on the thermal runaway of lithium ion battery (Z. Huang et al., 2021)	China	Runaway (TR) of Lithium-Ion Batteries with Various States of Charge (SOC) and Assessing Its Impact on New Batteries	Experimental	The study involved measuring the surface temperature of the batteries and analyzing the cooling effects	The sample consisted of batteries with SOC ranging from 25% to 100%	The research demonstrated that liquid nitrogen could effectively delay and cool thermal runaway in the batteries, with heat utilization efficiency decreasing as the mass of liquid nitrogen sprayed increased.

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A5	Study on the Effectiveness of Water Mist on Suppressing Thermal Runaway in LiFePO4 Batteries (Q. Li et al., 2023)	China	Assessing the Effectiveness of Water Mist in Preventing and Cooling Thermal Runaway in LiFePO4 Batteries Due to Thermal Abuse	Experimental	Data were collected via direct observation of temperature, pressure, and mass changes using thermocouples, pressure sensors, and electronic scales.	The study used LiFePO4 batteries with a capacity of 100 Ah, an individual mass of 1980 g, and dimensions of 2160 mm × 1350 mm × 35 mm	The water mist was found to be effective in suppressing the initiation of thermal runaway and had a significant cooling effect on the LiFePO4 batteries, resulting in rapid temperature reduction and decreased accumulated heat density.
A6	Experimental investigation into the use of emergency spray on suppression of battery thermal runaway (Y. Huang et al., 2021)	China	Exploring the Use of Emergency Sprays as a Cooling Method to Suppress Thermal Runaway in Lithium-Ion Batteries	Experimental	Data were collected using thermocouples to measure battery temperature and a spray system for cooling.	The study utilized 18650 lithium-ion batteries, each weighing 47 ± 0.5 g, with a 3300 mAh capacity and 3.6 V voltage.	The research showed that emergency sprays significantly lower battery temperature, preventing thermal runaway and inhibiting the heating process during TR conditions.
A7	Full-Scale Experimental Study on the Combustion Behavior of Lithium Ion Battery Pack Used for Electric Vehicle (H. Li et al., 2020)	China	Investigating the Fire Hazards of Lithium-Ion Battery Packs Used in Electric Vehicles Through Full-Scale Thermal Runaway Testing	Experimental	Data were collected using thermocouples to record temperature variations, along with digital video cameras and infrared imagers to document the burning behavior.	The study utilized a battery pack consisting of multiple lithium-ion battery modules.	The research identified three burning stages: thermal runaway initiation, propagation between cells, and fire extinguishing, revealing water's limited internal cooling effect.
A8	Experimental Study on Different Extinguishing Agents for Fire of Lithium Ion Batteries for Electric Mobility (Palma et al., 2023)	Italy	Determining the Most Efficient Fire Extinguishing Agent for Lithium-Ion Battery Fires Used in Electric Mobility.	Experimental	This study involved experimental tests using Kokam SPLB pouch cells with a capacity of 40 Ah, evaluating four different extinguishing agents: Water, F500 Foam, AVD.	The study utilized 11 Kokam SPLB pouch cells, each with a capacity of 40 Ah and a nominal voltage of 3.7 V.	The research demonstrated that pure water is the most efficient extinguishing agent for lithium-ion battery fires, followed by a mixture of water with F500 in spray and mist forms.
A9	Electric vehicles fire protection during charge operation through Vanadium-air flow battery technology (Barelli et al., 2021)	Italy	The study proposes a Vanadium-Air flow battery system for charging EVs and enhancing fire safety.	Experimental	The study combined initial experiments and CFD simulations to assess Vanadium-Air flow batteries' performance and protective enclosure strategies.	Simulations included models of electric vehicles across various categories (LCR, HCR, LCC, HCC) to calculate the volume of the protected enclosure and the battery requirements.	The Vanadium-Air flow battery system simultaneously charges EVs and enhances fire protection by reducing oxygen concentration, also serving as energy storage.

Table 4. Mapping Fire Management for Electric Vehicles

Article code	Type of Extinguisher					Method of Use		Experiment Results	
	Solid	**Liquid**	**Gas**	**Foam**	**Chemical**	**Single**	**Combination**	**Reducing Temperature**	**Extinguishing fire**
A1	Fire Blanket	Water spray & water mist		Compressed air foam			✓	✓	✓
A2		Water mist	Carbon dioxide (CO2)		Dodekafluoro-2-methylpentan-3-one (C6F12O)		✓	✓	✓
A3	Fire Blanket	Water	heptafluoropropane (HFC-227ea)				✓	✓	✓
A4		Liquid nitrogen				✓		✓	
A5		Water mist				✓		✓	
A6		Water-based spray				✓		✓	
A7		Water				✓			✓
		Water				✓		✓	✓
A8		Aqueous Vermiculite Dispersion (AVD)				✓			✓
				Foam		✓			✓
					F500	✓		✓	✓
A9			Combination battery nitrogen gas VAB				✓	✓	

RESULTS AND DISCUSSION

Group of Extinguishing Agents

The articles (Zhao, Hu, Meng, Mi, Wang, & Wang, 2024) and (Lim et al., 2021) discuss the group of extinguishing agents from the solid type, specifically fire blankets. Fire blankets have proven effective in extinguishing fires in the early stages of electric vehicle fires by cutting off the oxygen supply and preventing the spread of fire to the surrounding environment.

All articles highlight the group of extinguishing agents from the liquid type, such as water spray, water mist, liquid nitrogen, and Aqueous Vermiculite Dispersion (AVD), showing variations based on mechanisms and application conditions. Water spray is effective in lowering temperature and extinguishing fire, although it can sometimes cause thermal runaway if water seeps into the battery cells. Water mist can reduce temperature and smoke and functions well in preventing the spread of fire while aiding in cooling; however, it may not always be able to extinguish the fire completely. On the other hand, liquid nitrogen is effective in preventing thermal runaway in lithium-ion batteries, especially if used before the surface temperature of the battery reaches the critical temperature range of 270.2°C to 170.2°C. Liquid nitrogen lowers temperature through film boiling and radiation mechanisms, with decreased effectiveness when temperatures exceed critical limits. Research indicates that these methods have potential in addressing fires, particularly related to lithium-ion batteries, but their effectiveness is highly dependent on application methods and the specific conditions of the fire.

The articles (Zhang et al., 2020) and (Barelli et al., 2021) discuss the group of extinguishing agents from the gas type, such as carbon dioxide (CO2), heptafluoropropane (HFC-227ea), and the combination battery nitrogen gas VAB (Vanadium Air Flow Battery), in an effort to extinguish fires in lithium-ion batteries. The use of carbon dioxide (CO2) has been shown to reduce oxygen concentration, although its reaction is relatively slow.

The articles (Zhao, Hu, Meng, Mi, Wang, & Wang, 2024) dan (Palma et al., 2023) discuss the group of extinguishing agents from the foam type, such as compressed air foam. Compressed air foam has proven highly effective in extinguishing fires in lithium-ion batteries in electric vehicles. In experiments conducted, compressed air foam was able to extinguish fires quickly, with an average cooling rate of -9.8 °C per second.

The articles (Zhang et al., 2020) dan (Palma et al., 2023) discuss the group of extinguishing agents from the chemical type, such as dodecafluoro-2-methylpentan-3-one (C6F12O) and F500. Dodecafluoro-2-methylpentan-3-one (C6F12O) and F500 are fire extinguishing agents used to extinguish lithium-ion (Li-ion) battery fires. C6F12O, also known as FK-5-1-12, can extinguish Li-ion battery fires quickly without the risk of re-ignition; however, its cooling effect is not sufficient, necessitating additional cooling measures to prevent overheating after extinguishment. Meanwhile, F500, which is a mixture of water with a special extinguishing agent, demonstrates high efficiency in extinguishing Li-ion battery fires, particularly due to its superior cooling ability compared to gas-based extinguishing agents like CO2 or HFC-227ea. F500 is effective in reducing the duration of the extinguishing phase and the amount of agent required, demonstrating significant capability in rapidly lowering fire temperature.

Methods of Use

The methods of using extinguishing agents can be carried out either singly or in combination. Single methods are found in the articles (Z. Huang et al., 2021), (Q. Li et al., 2023), (Y. Huang et al., 2021), (H. Li et al., 2020), (Palma et al., 2023). The extinguishing agents used singly include liquid nitrogen, water mist, water-based sprays, Aqueous Vermiculite Dispersion (AVD), foam, and F500, each having various effectiveness and limitations in addressing lithium-ion battery fires. Water and foam are very effective in extinguishing fire and quickly lowering temperatures; however, they require advanced temperature control to prevent re-ignition. AVD shows good insulation capability but may require large quantities and is less effective in rapid cooling. F500 is efficient in extinguishing fire but needs to be combined with cooling agents for optimal effect. Spray methods, especially with water, are effective for cooling and extinguishing fires, but they require precise timing and duration management to maximize their effectiveness.

On the other hand, the use of combination methods is discussed in the articles (Zhao, Hu, Meng, Mi, Wang, & Wang, 2024), (Zhang et al., 2020), (Lim et al., 2021) dan (Barelli et al., 2021). The combination of extinguishing agents for lithium-ion (Li-ion) batteries in electric vehicles (EVs) has proven effective in extinguishing fires and controlling heat. Fire blankets, which are effective for oxygen isolation and direct fire extinguishment, do not fully stop thermal runaway. Water sprays and water mist are effective in cooling and reducing temperatures, thereby lowering the risk of re-ignition. Compressed air foam quickly extinguishes fire and significantly lowers temperatures. The simultaneous use of CO_2 and HFC-227ea offers rapid fire extinguishment and effective cooling, while CO_2 reduces the oxygen concentration around the fire. $C_6F_{12}O$ extinguishes fire quickly but requires additional cooling, typically through a combination with water mist.

Experiment results

All the articles reviewed in this study indicate that the effectiveness of extinguishing agents in lowering temperatures is crucial for addressing fire hazards related to electric vehicles, particularly those caused by thermal runaway in lithium-ion batteries. The use of compressed air foam demonstrates rapid and significant temperature reduction, with an average cooling rate of about -9.8 °C per second. Similarly, water mist is more effective in lowering peak temperatures, especially in the rear areas of vehicles that are closer to the fire source.

Limitations

In conducting a scoping review based on the Joanna Briggs Institute (JBI) assessment, several shortcomings were identified in the reviewed articles. A significant issue is the lack of methodological quality. The reviewed articles do not provide adequate descriptions of the research methods used, making it difficult for readers to assess the validity and reliability of the presented findings. Additionally, data incompleteness is also a major concern. Articles that do not provide complete data or contain incomplete data can hinder readers' ability to fully understand the topics discussed.

Conclusion

Fire management strategies for electric vehicles underscore the varied effectiveness of different extinguishing agents, ranging from fire blankets to F500. The combination of extinguishing techniques, such as using fire blankets with cooling agents or CO_2 with water mist, demonstrates high efficiency in extinguishing fires and managing temperatures. However, a comprehensive strategy is needed to prevent re-ignition and address thermal runaway. For instance, applying nitrogen combined with VAB (Vanadium Air Flow Battery) provides fire prevention and thermal control for Li-ion batteries. This study finds that the best way to reduce the risk of re-ignition in lithium-ion batteries is to select appropriate extinguishing agents and use effective cooling methods. This is crucial for ensuring the safety of electric vehicles.

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