Active Fire Protection Strategies for EVs and Charging Systems

Omprakash Thakare[1], Ajay Kumar Gupta[2], Arman Sarin[3], Sunik Kumar Sharma[4], Tarun Sonwani[5]
[1]*Assistant Professor, Department of Mechanical Engineering, Shri Rawatpura Sarkar University, Raipur, Chhattisgarh, India*
[2]*Associate Professor, Department of Mechanical Engineering, Shri Rawatpura Sarkar University, Raipur, Chhattisgarh, India*
[3]*Research Scholar, Department of Health Safety and Environmental Engineering, Shri Rawatpura Sarkar University, Raipur, Chhattisgarh, India*
[4,5]*Assistant Professor, Department of Mechanical Engineering, Shri Rawatpura Sarkar University, Raipur, Chhattisgarh, India*

Abstract- **The electrification of transportation has led to a rapid expansion of the electric vehicle (EV) market, driven by lower operational costs and environmental benefits. However, concerns over EV fire hazards have grown due to numerous reported incidents. This study conducts a Hazard and Operability (HAZOP) analysis of EV components and a failure analysis of lithium-ion batteries to identify potential risks. Additionally, an evaluation of current fire suppression systems and regulatory standards in India and internationally reveals a focus on fire prevention and thermal management, with limited emphasis on post-ignition fire protection and real-time suppression capabilities. To bridge this critical gap, the study proposes a novel, target-specific fire mitigation framework. This includes the development of an integrated fire detection and suppression system designed to address the distinct operational conditions of EVs.**

Keywords: Electric Vehicle Fire, Fire Suppression System.

I. INTRODUCTION

The transportation sector is a major contributor to greenhouse gas emissions, with traditional gasoline and diesel engines emitting large quantities of carbon dioxide (CO_2) and pollutants. As climate change becomes an urgent global issue, electric vehicles offer a cleaner and more sustainable transportation solution. EVs produce zero tailpipe emissions and, when charged using renewable energy sources, further reduce their carbon footprint. Governments and organizations worldwide have committed to reducing carbon emissions, with many implementing stringent regulations on vehicle emissions. As a result, automakers are investing heavily in EV production to comply with these regulations and contribute to a more sustainable future. One of the most critical factors driving EV adoption is the significant progress made in battery technology, particularly lithium-ion batteries. Improvements in energy density, charging speed, and battery lifespan have enhanced the viability of electric vehicles. Moreover, innovations in regenerative braking, powertrain efficiency, and smart vehicle integration have made EVs more attractive to consumers. Furthermore, the development of fast-charging networks, wireless charging, and battery-swapping technologies has addressed one of the primary concerns surrounding EV adoption—charging infrastructure. These advancements have significantly reduced range anxiety, making EVs a practical alternative to traditional ICE vehicles.

Governments across the globe have played a crucial role in accelerating EV adoption by implementing supportive policies. Many countries have introduced subsidies for EV purchases, tax exemptions, and incentives for manufacturers to invest in electric mobility. Some have even set ambitious targets to phase out gasoline-powered vehicles within the next few decades.

In addition to consumer incentives, governments have invested in EV infrastructure, such as charging stations, battery recycling programs, and research initiatives aimed at improving battery technology.

Stringent emission regulations and mandates for corporate fleets to transition to electric mobility have also contributed to the growing adoption of EVs.

The concept of electric propulsion in vehicles dates to the early 1800s when inventors sought alternatives to steam and gasoline engines. Some of the first prototypes of electric cars were developed in the mid-19th century, offering a quiet, clean, and efficient means of transportation. By the late 1800s and early 1900s, electric cars had gained popularity, particularly in urban areas, where they were favoured over gasoline-powered vehicles due to their simplicity and ease of operation.

However, the rise of mass production, notably pioneered by Henry Ford's assembly line in 1913, made gasoline-powered cars more affordable and accessible. Additionally, the development of internal combustion engines with greater range and speed led to the decline of electric vehicles. The lack of reliable battery technology and limited charging infrastructure further hampered their adoption, causing a near disappearance of EVs from the mainstream automotive industry for much of the 20th century.

The resurgence of EV interest began in the late 20th century when concerns about air pollution, oil dependency, and environmental degradation became more pronounced. The global oil crises of the 1970s highlighted the vulnerabilities of fossil fuel dependence, prompting research into alternative energy sources. This renewed interest culminated in the development of hybrid and fully electric vehicles in the early 2000s. With Tesla's introduction of high-performance electric cars in the 2010s, the modern EV market started gaining significant traction, bringing EVs to the forefront of mainstream transportation.

II. LITRATURE REVIEW

Jiajia Xu (2020) investigated fire. Three different extinguishing agents including CO_2, HFC-227ea and water mist were adopted. The results show that each agent can inhibit the combustion of the combustible gases and jet fire of the cell. However, a flame is observed during the release of CO_2 and HFC-227ea, while no flame is observed in the case with water mist, which means that water mist shows a better suppressive effect than the other two extinguishing agents. The absence of these extinguishing agents was often accompanied with black smoke and violent jet fire. Moreover, the peak average temperatures before the extinguishing agents were depleted were 43, 75 and 133 °C lower, respectively, than that in the situation without an extinguishing agent. These results indicate that water mist has the best cooling effect comparing with CO_2 and HFC-227ea, which has significant implications for the design of a LIB fire protection system.

Zonghou Huang (2021) investigated TR is prevented by applying LN before the surface temperature (Tw) is reached the critical TR suppression temperature. The delaying effect of LN on TR is weakened with increasing the surface temperature of the battery. Only 29.3 g of LN sprayed on the battery reduces the temperature of 9.24 Wh LIB from about 700 °C to less than 100 °C within 80 s. While the cooling effect of LN to the inside the battery becomes more superior as the application time prolongs. Furthermore, the calculated average cooling rate decreases from 10.3 °C/s to 2.84 °C/s when Tw reduces from 800 °C to 0 °C, illustrating that the cooling effect of LN is weakened with decreasing Tw.

I.V. Zabelin (2024) have developed a novel self-activating hydrate extinguisher and tested it in different types of fires. The extinguisher stops the flame combustion at the moment of activation due to the shock wave produced by its burst. Then the gas hydrate spreads over the surface of the burning fuel, its ice shell melts, thus reducing the temperature in the seat of the fire and releasing the inert gas. The experiments have shown that the extinguisher response time can be adjusted by varying such parameters as the mass of hydrate and the volume of the free space in the extinguisher, the amount of added water, and the type of mechanical impact on the extinguisher. also developed a conceptual framework for the production of self-activating hydrate extinguishers and their delivery to the seat of the fire.

III PROBLEM IDENTIFICATON

The shift from internal combustion engine (ICE) vehicles to electric vehicles (EVs) has brought significant technological progress. However, this transition also introduces new safety concerns, especially related to fire hazards. A primary concern involves the lithium-ion batteries used in EVs, which operate at high voltages. These battery systems, while efficient, carry a risk of thermal runaway. Thermal runaway can occur when the battery overheats, leading to a chain reaction of heat generation. In addition, short circuits within the battery can spark fires. Overcharging is another critical issue that may trigger battery failure or ignition. Mechanical damage to battery cells, such as from crashes or road debris, can also lead to dangerous fire situations. In extreme cases, these conditions can even cause the battery to explode. While international and national standards like IEC 61851 and AIS 138 exist, they are not fully comprehensive.

Current fire safety regulations often lack integration across the entire EV ecosystem. Fire safety measures tend to focus on response rather than prevention. Implementation of fire protection strategies varies significantly between EV manufacturers. Similarly, charging infrastructure safety practices are inconsistent across different regions and countries. There is no unified fire protection system that covers prevention, early detection, suppression, and recovery. As a result, fire safety in EVs remains fragmented and reactive. This inconsistency highlights a serious gap between evolving technology and regulatory frameworks. A thorough and systematic study of EV fire risks is urgently needed. Developing an integrated and proactive fire safety strategy will help close this gap. Ultimately, improving EV fire safety is vital for protecting people and property and for maintaining public confidence in electric transportation.

IV METHODOLOGY

4.1 Electric Vehicle Architecture and Battery System

Electric vehicles (Evs) operate using a combination of high-voltage battery systems, power electronics, and electric drive units. At the heart of most Evs lies the lithium-ion battery pack, which is favored for its high energy density, lightweight characteristics, and efficiency. These battery packs are typically placed under the floor of the vehicle in a skateboard configuration, providing structural rigidity and a low center of gravity. However, this design also means that any compromise in the battery pack’s integrity—due to mechanical impact, overcharging, or internal failure—can pose a serious fire hazard. Electric vehicles (Evs) are designed with a unique architecture that differs significantly from traditional internal combustion engine (ICE) vehicles. The core of an EV is centered around its electric powertrain, battery system, and integrated control mechanisms that ensure efficient energy utilization. The architecture of an EV involves various components working seamlessly to deliver a clean, efficient, and high-performance driving experience.

Electric Vehicle is propelled by one or more electric motors using energy stored in rechargeable batteries, instead of burning petrol or diesel internally and exhausting fumes. They can be either partially or fully powered on electric power.

4.2 Components of Electrical Vehicle

4.2.1 Chassis:

It is a self-contained platform with electronic motors, battery, and driving components integrated into it, which can be scaled to various sizes and topped with a variety of bodies. The **chassis** of an electric vehicle (EV) plays a crucial role in ensuring structural integrity, safety, and optimal performance. Unlike traditional internal combustion engine (ICE) vehicles, EV chassis are often purpose-built to accommodate electric powertrains, battery packs, and modern design features.

Fig 4.1 Electrical vehicle chassis

4.2.2 Battery pack:

Battery Pack is used to power the electric motors of a BEV or PHEV. These batteries are rechargeable & are typically Lithium-ion batteries. They are specifically designed for a high ampere-hour (or kilowatt-hour) capacity. Batteries for electric vehicles are characterized by their relatively high power-to-weight ratio, specific energy and energy density; smaller, lighter batteries are desirable because they reduce the weight of the vehicle and therefore improve its performance.

4.2.3 Invertor:
The inverter converts the high-voltage, high- current DC electricity from the batteries and converts it to AC electricity for the 3-phase induction motor. It also supplies current to the battery pack for recharging during regenerative break.

4.2.4 Phase Induction Motor:

It is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. They are widely used in electric vehicles.

4.3 Case study of fires accidents in Electric Vehicles
Incidents involving EV may also lead to secondary thermal events resulting from the overall amount of damage done to the LIB. There are, namely, cases in which reignition transpired once or multiple times. An example of this is a Tesla Model S that crashed in Florida, USA, by impacting a wall at 140 km/h. The impact led to the vehicle being engulfed in flames. After the fire had been subdued and the vehicle was removed from the scene, it reignited. When the destroyed vehicle finally arrived at the two yards, it reignited once more. This is of concern for post-crash handlers, who normally do not have the tools or training to handle such events safely.

4.4. Battery-related Fire Risks (Thermal Runaway, Short Circuit, Overcharging):

Over the last decade, the electric vehicle (EV) has significantly changed the car industry globally, driven by the fast development of Li-ion battery technology. Lithium-ion batteries have attracted interest from academia and industry due to their high power; energy densities and long cycle lives compared to other battery technologies. Additionally, a lower weight makes the LIB most suitable for vehicles as it can promote transportation efficiency. The energy of lithium-ion batteries (LIBs) is housed within individual battery cells. A lithium-ion cell consists of a cathode, an anode, separator, and electrolyte. Each cell has one positive and one negative terminal.

These terminals are connected to thin metal foil that has been coated with electrochemically active material. The active material for the negative and positive side of the battery is referred to as anode and cathode material, respectively. The electrolyte enables the movement of lithium ions between the electrodes, while the separator fits between the anode and cathode preventing shorting between the two electrodes but permitting ion transfer. During the discharge reaction, lithium ions move from the anode and insert into the voids between layers of cathode crystals (the process named intercalation). Upon charging, lithium ions move from the cathode on the positive side of the battery and insert into the anode. During the initial charge, intercalated lithium ions react immediately with the solvent of the electrolyte and form a passivation layer on the anode, Solid-Electrolyte Interphase (SEI), which is permeable to lithium ions but not to the electrolyte. To supply the desired power and energy from a battery system (an energy storage system), the cells are connected in parallel to increase the capacity or in series to raise the voltage. A battery system usually consists of a number of battery packs, which are made of multiple battery modules, each containing a number of cells with series and/or parallel configuration.

4.5 Fire hazards associated with Lithium-Ion Batteries:
When exothermic chemical reactions are generating more heat than is being dissipated, the LIB enters a so-called thermal runaway condition. Thermal runaway is triggered by a chain of chemical reactions inside the battery resulting in an accelerated increase of internal temperature. Specifically, decomposition of SEI (Solid Electrolyte Interface) layer [The interface between electrolyte and current collectors. This is where electron exchange occurs.] and reactions between electrolyte and anode is followed by melting of the separator and breakdown of the cathode material. Battery temperature increases dramatically approximately at rate of 10ºC/min. The outcome can be that of complete combustion of the LIB accompanied by the release of gas, flying projectiles and powerful jet flames.

LIBs are designed to receive and store a certain amount of energy over a specific amount of time. When these limits are exceeded, because of charging too quickly or overcharging, the cell performance may degrade, or the cell may even fail. The charge level of batteries is normally defined in terms of state of charge (SOC). Their operational limits may be defined from 0-100%, which means that a battery at 100% SOC is considered fully charged to its rated capacity. Overcharging may be realized when the cell voltage is incorrectly detected by the charging control system, when the charger breaks down or when the wrong charger is used. When overcharging, the anode material can become overly lithiated. As a result, lithium intercalation ceases and lithium metal deposits on the anode. These deposits may grow into metallic fingers commonly referred to as dendrites. As they grow, they can reach the point where they penetrate the separator and cause an internal short circuit. The opposite happens at the cathode. Here overcharging may result in it becoming de-lithiated to the point where the cathode decomposes thermally and generates heat.

When the LIB is discharged, lithium-ions flow from the negative current collector and anode to the positive current collector and cathode. If the level of discharge becomes too great however, the negative current collector, which consists of copper, can dissolve. As a result, small conductive copper particles are released in the electrolyte which increase the risk for an internal short circuit. It can also lead to the evolution of hydrogen and oxygen, cell venting and plating on the cathode. Over-discharge abuse occurs when discharging battery cells below their minimum voltage. In the unlikely event where four battery cells are in series, and one of them is completely discharged (0V), this could lead to the empty cell being discharged even further.

4.6 Charging Station Fire Risks:

As electric vehicles (EVs) become increasingly popular, the deployment of EV charging stations (EVSE) is expanding rapidly across public, private, and commercial locations. While these charging infrastructures are critical to EV adoption, they also introduce a unique set of fire risks, especially when not designed, installed, or maintained properly. Fires associated with charging stations can pose hazards not only to vehicles but also to surrounding infrastructure and public safety.

4.7 Electrical and Electronic Component Failures:

Apart from battery-related hazards, electric vehicles (EVs) rely on a wide array of electrical and electronic components that are critical to power distribution, energy conversion, and system control. Failures in these systems can also act as ignition sources or contribute to fire development if not properly protected or monitored. EVs operate at voltages ranging from 300V to over 800V, significantly higher than conventional 12V systems in internal combustion engine (ICE) vehicles. This high-voltage architecture involves inverters, DC-DC converters, onboard chargers, and power distribution units (PDUs). If insulation breaks down due to wear, overheating, or contamination, electric arcs can form, which generate intense local heat and may ignite surrounding materials, particularly under confined or enclosed conditions.

Over time, the insulation on wires, connectors, and busbars may degrade due to thermal cycling, moisture ingress, or mechanical stress. Degraded insulation increases the risk of leakage currents, which not only impact system efficiency but can also heat conductive pathways and trigger localized ignition. In severe cases, electrical tracking and short circuits between adjacent conductors can lead to fires. Loose, worn-out, or improperly mated connectors are common sources of electrical failure in EVs. Poor contact increases electrical resistance, leading to heat buildup during high current flow. If not detected early, this heat can melt connector housings, ignite plastic insulation, or degrade critical circuit paths. Failures in connectors are particularly dangerous because they can be intermittent, escaping detection by standard diagnostics until failure occurs under load.

The Battery Management System (BMS), Vehicle Control Unit (VCU), and thermal control modules are responsible for managing safe energy flow and thermal regulation. A software malfunction or sensor error could result in undetected overheating, improper current distribution, or failure to initiate shutdown procedures in the event of a fault. Although rare, firmware bugs, sensor drift, or inadequate response thresholds in these control units can delay fire mitigation actions, allowing thermal conditions to escalate.

V CONCLUSION

This study demonstrates that ergonomically informed interventions can significantly reduce musculoskeletal disorder (MSD) risks among data center technicians. The implementation of tailored ergonomic practicessuch as posture training, lifting technique instruction, work-rest cycles, and ergonomic workstation designs—led to measurable improvements in worker health, task efficiency, and overall job satisfaction. Quantitative analysis highlighted a 58% decrease in MSD incidents and notable improvements in task completion time and stress levels. These findings confirm that investing in ergonomic solutions is not only essential for the well-being of employees but also strategically advantageous for operational efficiency and sustainability in data center environments.

V FUTURE SCOPE

- Technology-Driven Ergonomics: Future studies can integrate wearable sensors and AI-driven analytics to monitor posture, movement, and fatigue in real-time, enabling proactive interventions.
- Broader Applicability: Expanding ergonomic assessments to include other high-risk sectors such as warehouse logistics, manufacturing, or healthcare IT facilities would help validate the universality of the proposed interventions.
- Long-Term Impact Evaluation: Longitudinal studies are needed to assess the sustained benefits of ergonomic programs and determine their influence on long-term injury prevention and employee retention.
- Policy Development: Collaboration with regulatory bodies can help translate research findings into ergonomic standards and best practices tailored to data centers.
- Virtual and Augmented Reality (VR/AR): Exploring the role of VR/AR-based training simulations could revolutionize how technicians learn safe techniques without exposing themselves to risk.

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