HYBRID VEHICLE BATTERY FIRES
Experimental Insights and Risk Evalution

by

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This study investigates the fire behavior of lithium-ion batteries used in hybrid electric vehicles under gasoline-induced thermal conditions. In the experimental set-up, 2 L of gasoline were ignited to analyze and compare the thermal responses of a 6 cell 18650 cylindrical battery pack and a prismatic battery. Temperature changes were recorded at T_1 and T_2 points using K-type thermocouples, and the thermal reactions of each battery type were evaluated. Both batteries exhibited safety valve activation, thermal runaway, and jet flame emissions. The prismatic battery initially showed higher resistance, yet eventually underwent a similar failure sequence. Maximum temperatures reached 981.3 °C at T_2 and 765.4 °C at T_1, indicating the severity of the thermal runaway process. The findings demonstrate that hydrocarbon fuel significantly intensifies battery reactions and highlight the necessity of improved fire safety strategies in hybrid systems. This study provides a valuable foundation for future research on battery safety and fire risk mitigation in multi-energy vehicle configurations.

Key words: *fire, hybrid electric vehicle, lithium ion battery, fire safety*

Introduction

In the past decade, there has been a significant increase in the popularity of hybrid electric vehicles (HEV) [1]. This rise can be attributed in part to their enhanced fuel efficiency and reduced environmental impact compared to traditional gasoline-powered vehicles. The HEV combine an internal combustion engine with an electric motor, thereby improving energy efficiency and lowering emissions. As the automotive industry evolves, HEV have become an integral component of the push towards more sustainable transportation solutions. Despite their advantages, hybrid vehicles are not without risks. One growing area of concern is the potential for fire incidents involving HEV. Vehicle fires pose serious threats to passengers, first responders, and the general public, potentially resulting in catastrophic consequences. Although vehicle fires are not a new phenomenon, the battery systems in HEV introduce a new dimension the risk landscape. The common causes of vehicle fires include fuel system leaks, electrical system failures, spilled fluids, overheated engines, overheated catalytic converters, hybrid and electric vehicle batteries, arson, and traffic accidents. Fuel system leaks, particularly those involving flammable liquids such as gasoline, significantly increase the risk of fire. Electrical system failures can lead to fires due to short circuits and overloads. Spilled fluids heighten the risk

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when they come into contact with hot surfaces. Overheated engines and catalytic converters can cause fires due to excessively high temperatures. Hybrid and electric vehicle batteries pose an increased fire risk due to thermal runaway events. Additionally, arson and traffic accidents are also common causes of vehicle fires. For modern vehicles, the mass of plastics used in vehicle ranges from 100-200 kg [2], which is larger than that of gasoline (less than 50 kg). As the heat of combustion for common plastics without fire retardants (*e.g.* 38.4 MJ/kg for polyethylene and 27 MJ/kg for PS) is not very different from the gasoline (47 MJ/kg), the total heat release from burning plastic components may have a major contribution the vehicle fire, especially if the gasoline tank is not full. Nevertheless, there is no major difference between ICEV and EV in terms of plastic components, so that the major difference is their power system and the fuel (gasoline *vs*. battery) [3].

Since the lithium-ion battery (LIB) became the dominant power source for HEV a decade ago, the fire risk and LIB has become a significant safety issue. This is related to the increasing scale of deployment and energy density of the battery pack. The word Lithium (as a chemical element) itself has questions of safety tagged to it [4-6]. When a LIB is exposed to an external impact and experienced extreme operating conditions, it can break, eject sparks, flammable gases and toxic smokes which can be further ignited and lead to steady combustion, jet flames or a gas explosion [7-9]. Recent high profile incidents involving hybrid vehicle fires have raised questions about the safety of these vehicles, particularly concerning their electrical systems and battery components. The HEV utilize a combination of electricity and gasoline as their power sources. They can transfer excess chemical energy from fossil fuels into electrical energy via the internal combustion engine, which is then stored in the battery pack [10]. In other words, hybrid vehicles operate with two distinct energy systems: an electrical energy system and a traditional internal combustion engine powered by fossil fuels. The exhaust system of these vehicles can reach temperatures high enough to ignite the flammable fuels present in the vehicle [3]. This convergence of two distinct fire risks presents a unique safety challenge. The presence of gasoline can significantly influence fires involving HEV. Here are some key points:

Gasoline is highly flammable and can exacerbate the intensity and spread of a fire. When a battery fire occurs in a vehicle that also contains gasoline, the fire can quickly become more severe due to the additional fuel source [11]. The combustion of gasoline releases toxic gases such as CO, which can combine with the toxic gases released from a battery fire, such as hydrogen fluoride and other harmful compounds [12]. This combination can create a highly dangerous environment for both occupants and emergency responders. Gasoline can increase the heat release rate (HRR) of a fire. The HRR is a critical factor in determining the intensity and hazard of a fire. The presence of gasoline can lead to a more rapid and intense fire, making it more challenging to control and extinguish [13]. The combination of gasoline and battery fires can increase the risk of explosions. Gasoline vapors are highly explosive, and when mixed with the gases released from a thermal runaway event in a battery, the likelihood of an explosion can be significantly higher [13]. Since the electrolyte is a flammable organic solvent, and the anode, cathode, and separator are made of combustible materials containing unstable lithium, a fire or explosion resulting from thermal runaway following physical, electrical, or thermal failure is possible [14]. Addressing this safety issue is crucial for broader adoption [14, 15].

The presence of gasoline complicates fire suppression efforts. Traditional methods for extinguishing gasoline fires may not be effective for battery fires, and vice versa. This dual challenge requires specialized approaches and equipment to manage the fire safely [16]. Understanding these factors is crucial for developing effective fire prevention and suppression strategies for vehicles that contain both gasoline and LIB. The unique configuration of HEV, incorporating both fuel-based and electric power sources, presents potential fire hazards distinct from those in conventional or fully electric vehicles. Numerous studies have demonstrated that LIB can continue to burn for days after sustaining fire damage. For instance, a study by Feng *et al.* [1] examined thermal runaway scenarios in LIB and observed that these batteries emit white smoke after fire damage, which can lead to explosions in the gas phase [17]. Similarly, Larsson *et al.* [18] reported that LIB reach high temperatures following fire damage, causing them to continue burning. Additionally, research by Doughty and Roth [19] highlighted that LIB release hazardous gases after fire damage, further increasing the fire risk. Based on the factors influencing the flame behavior of batteries, scientists have investigated battery flame suppression methods from various perspectives. These methods can largely be divided into two categories: active suppression [20, 21] and passive suppression [22, 23]. Active suppression provides a more direct suppression effect compared to passive suppression, but it may fail to achieve suppression in the initial phase and is more costly. Extinguishing fires in hybrid vehicles is more challenging due to the design of their batteries. While gasoline fires are highly hazardous, they involve a single reaction, whereas hybrid vehicle batteries act as a prolonged energy source, sustaining a continuous chain reaction process. This makes extinguishing hybrid vehicle fires even more difficult.

Experiment flow diagram and experimental set-up

Combustion tests involving LIB inherently carry significant risks and therefore, must be carefully designed and executed with safety as a top priority. The experimental environment must address potential hazards such as the thermal effects of jet flames, the release of toxic gases and smoke, injury risks caused by cell rupture or fragmentation, threats arising from the rapid vaporization of hydrocarbon fuels, and the explosion potential during fast combustion reactions. Accordingly, safety strategies should be integrated into both the structural and operational aspects of the experimental set-up. Throughout the entire process, including data collection, the use of independent and supportive personal protective equipment is mandatory. The experimental set-up is designed to allow for controlled combustion of both single-cell and multi-cell battery configurations. For HEV in particular, a modular system with interacting compartments has been developed to simulate realistic fire scenarios involving combinations of battery systems and hydrocarbon-based fuels. This modular approach enables the modelling of diverse fire behaviors under various conditions. While most studies in the literature focus solely on LIB fires, the combined effects of battery and fuel combustion in hybrid vehicles have not been sufficiently addressed. The interaction between these two distinct ignition sources can significantly intensify fire severity and propagation. Therefore, experimental investigations that examine the interaction between battery fires and fuel-induced fires are essential. These experiments aim to analyze not only the combustion behavior of different battery cell types but also the dynamic interaction of their combustion products under combined fire conditions.

In this context, the present study included the addition of 2 L of gasoline to the test set-up to induce and complement thermal runaway and jet flame reactions in the batteries. The schematic lay-out and dimensional specifications of the experimental system are provided in fig. 1. The gasoline combustion vessel is designed to simulate the burning of fuel spilled or retained within a specific volume. The grill iron represents the vehicle's underbody chassis and cavities and the steel casing functions as the outer protective layer of the battery block, maintaining the structural integrity of the set-up throughout the combustion process. These components are arranged to closely resemble real-world vehicle conditions while also ensuring the containment of the fire's effects within the set-up. During the experiment, temperature changes caused by heat transfer from the burning gasoline were monitored and compared between a six cell (parallel-connected) 18650 cylindrical battery pack and a prismatic battery. The differences in the rate of temperature increase per unit time between the two battery types were carefully observed, providing valuable insight into their respective thermal responses in fire conditions.

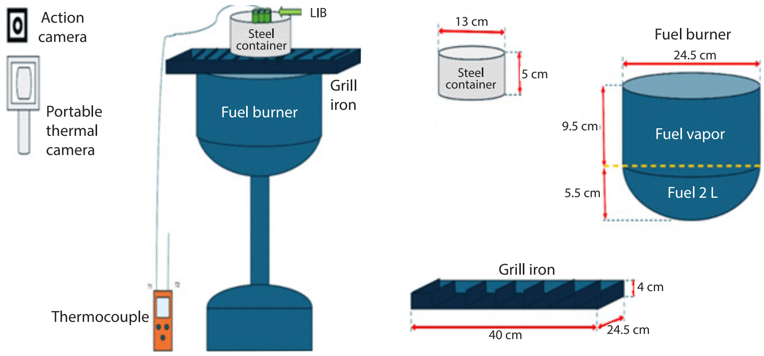


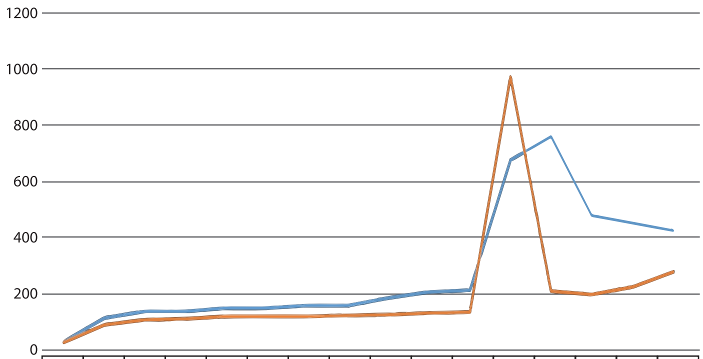
Figure 1. Experimental set-up for HEV

Experiment results and discussion

In this study, the experiment was initiated by igniting 2 L of gasoline placed in the fuel combustion chamber using a torch. The experimental set-up included both a prismatic type battery and a six cell 18650 cylindrical battery block observed together. Differences in the responses of the prismatic battery and the 18650 battery block to the propagation of heat from the fuel combustion were examined. Temperature changes in the six cell 18650 battery block were recorded using a *K*-type thermocouple attached at T_1, while temperature changes in the prismatic type battery were recorded using a *K*-type thermocouple attached at T_2. Throughout the experiment, the combustion reaction was allowed to proceed naturally without any intervention. The graphical data obtained from the experiment are presented in fig. 2.

The temperature values before the ignition of the fuel were 27.0 °C at T_1 and 24.5 °C at T_2. At the 7:46 minute mark of the experiment, these values increased to 112.0 °C at T_1 and 89.0 °C at T_2. In the subsequent stages of the experiment, the process progressed:

– At the 9:30 minute mark, the safety valve of the first cell in the 18650 battery block opened, with T_1 temperature recorded at 135.8 °C and T_2 at 107.8 °C.
– At the 9:38 minute mark, the safety valve of the second cell in the 18650 battery block opened, with T_1 temperature recorded at 136.5 °C and T_2 at 108.9 °C.
– At the 10:18 minute mark, the safety valve of the third cell in the 18650 battery block opened, with T_1 temperature recorded at 148.5 °C and T_2 at 117.6 °C.
– At the 10:19 minute mark, the safety valve of the fourth cell in the 18650 battery block opened, with T_1 temperature recorded at 149.8 °C and T_2 at 119.1 °C.
– At the 10:30 minute mark, the safety valve of the fifth cell in the 18650 battery block opened, with T_1 temperature recorded at 156.6 °C and *T*2 at 120.0 °C.
– At the 10:35 minute mark, the safety valve of the sixth cell in the 18650 battery block opened, with T_1 temperature recorded at 158.2 °C and T_2 at 123.1 °C, fig. 3(a).
– At the 10:57 minute mark, thermal runaway and jet flames lasting for 7 seconds were observed in the 18650 battery block, with T_1 temperature recorded at 184.6 °C and T_2 at 124.2 °C.
– At the 11:09 minute mark, thermal runaway and jet flames lasting for 9 seconds were observed in the 18650 battery block, with T_1 temperature recorded at 206.3 °C and T_2 at 131.7 °C.



	Pre-gasoline combustion 0	Temperature value 07:46	First safety plug release 09:30	Second safety plug release 09:38	Third safety plug release 10:18	Fourth safety plug release 10:19	Fifth safety plug release 10:30	Sixth safety plug release 10:35	Thermal runaway and jet flame 10:57	Thermal runaway and jet flame 11:09	Thermal runaway and jet flame 11:23	Highest temperature value for T2 13:25	Highest temperature value for T1 14:01	Safety valve release thermal runaway, and jet flame in pouch-type battery 21:56	Combustion continues in pouch-type battery 23:19	Combustion does not continue in pouch-type battery, gas emission present 25:32
T1-temperature value [°C]	27	112	135.8	136.5	148.5	149.8	156.6	158.2	184.6	206.3	211.6	681	765.4	481.5	454.6	425.8
T2-temperature value [°C]	24.5	89	107.8	108.9	117.6	119.1	120	123.1	124.2	131.7	133.4	981.3	208.9	197.4	225.2	277.5

Figure 2. Graphical representation of observations from the experiment: gasoline, prismatic type battery, and six cell 18650 cylindrical battery

(a) (b) (c)

(d) (e)

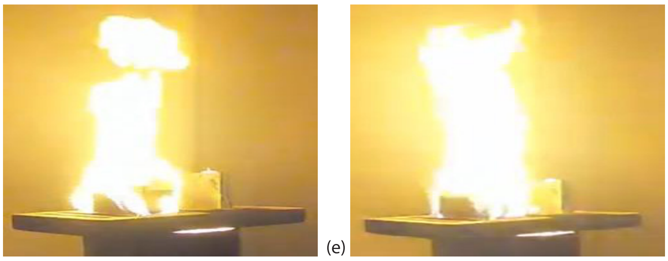


Figure 3. Images of the experimental set-up: gasoline combustion, six cell 18650 cylindrical battery, and prismatic type battery

- At the 11:23 minute mark, thermal runaway and jet flames lasting for 7 seconds were observed in the 18650 battery block, with T_1 temperature recorded at 211.6 °C and T_2 at 133.4 °C, fig. 3(b).
- At the 13:25 minute mark, the highest T_2 temperature in this experiment was recorded at 981.3 °C, while T_1 was measured at 681 °C, fig. 3(e).
- At the 14:01 minute mark, the highest T_1 temperature in this experiment was recorded at 765.4 °C, while T_2 was measured at 208.9 °C, fig. 3(d).
- At the 21:56 minute mark, the prismatic type battery exhibited safety valve opening, thermal runaway, and jet flames simultaneously, with T_1 temperature recorded at 481.5 °C and T_2 at 197.4 °C, fig. 3(c).

– At the 23:19 minute mark, combustion continued in the prismatic type battery, with T_1 temperature recorded at 454.6 °C and T_2 at 225.2 °C.
– At the 25:32 minute mark, combustion in the prismatic type battery had ceased, although a small amount of gas emission continued. The T_1 temperature was recorded at 425.8 °C, and T_2 at 277.5 °C. It was observed that all six 18650-type lithium-ion cells and the prismatic type battery had fully participated in the reaction process.

Conclusion

The experimental results clearly demonstrated that both the six cell 18650 cylindrical battery pack and the prismatic-type battery exhibited significant thermal responses when exposed to external heat generated by gasoline combustion. The sequential activation of safety valves in the 18650 cells and the gradual rise in temperature confirmed the propagation of thermal stress throughout the battery module. The peak temperature values recorded at T_2 (981.3 °C) and T_1 (765.4 °C) reflect the severity of the thermal runaway process and the magnitude of the associated energy release. Although the prismatic battery initially showed higher resistance to heat propagation, it eventually displayed similar failure behavior, including safety valve release, thermal runaway, and jet flame emission.

The delayed response observed in the prismatic battery compared to the 18650 cells suggests that structural or design differences may influence thermal tolerance. Overall, the study confirms that heat generated by hydrocarbon fuel combustion is sufficient to trigger critical battery reactions in HEV configurations. The findings emphasize the importance of improving thermal management systems and fire suppression strategies, particularly in vehicles that incorporate multiple battery chemistries. These results offer a valuable foundation for future research aimed at enhancing battery safety and minimizing fire-related risks under real-world conditions.

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