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Review

Review of Flame Behavior and Its Suppression during Thermal Runaway in Lithium-Ion Batteries

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Abstract: Lithium-ion batteries (LIBs) are extensively utilized in electric vehicles (EVs), energy storage systems, and related fields due to their superior performance and high energy density. However, battery-related incidents, particularly fires, are increasingly common. This paper aims to first summarize the flame behavior of LIBs and then thoroughly examine the factors influencing this behavior. Based on these factors, methods for suppressing LIB flames are identified. The factors affecting flame behavior are categorized into two groups: internal and external. The paper then reviews the flame behavior within battery modules, particularly in confined spaces, from both experimental and simulation perspectives. Furthermore, methods for suppressing battery flames are classified into active and passive techniques, allowing for a more comprehensive analysis of their effectiveness. The paper concludes with a summary and outlook, offering new insights for future research and contributing to the development of safer and more efficient battery systems.

Keywords: lithium-ion battery; flame behavior; thermal runaway; suppression

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Citation: Mao, Y.; Chen, Y.; Chen, M. Review of Flame Behavior and Its Suppression during Thermal Runaway in Lithium-Ion Batteries. *Batteries* **2024**, *10*, 307. https://doi.org/10.3390/batteries10090307

Academic Editor: Vilas Pol

Received: 30 July 2024
Revised: 25 August 2024
Accepted: 29 August 2024
Published: 30 August 2024

1. Introduction

In 1976, Whittingham et al. [1] proposed a new battery operating principle, intercalation, which laid a solid foundation for the subsequent commercialization of lithium-ion batteries (LIBs). Nowadays, LIBs have been widely used in various fields, especially in electric vehicles (EVs), because of their long cycle life, high energy density, and high charging speed [2–4]. However, battery modules with higher energy densities tend to have lower thermal stability, which has led to a global rise in fire accidents in EVs, posing a serious threat to the personal safety of passengers [5,6]. Whereas most of the battery thermal runaway (TR) occur in confined structures, such as the top plate of an electric vehicle (EV) [7–9], this battery flame behavior, which occurs in confined spaces, tends to be more violent and has the potential to explode, leading to the structural failure of the roof, ultimately posing a significant hazard to the environment and nearby personnel [10]. Flames can affect the electrochemical processes within the cell by raising its temperature and ultimately exacerbate thermal runaway propagation (TRP), especially in confined space where this behavior is more pronounced [11]. Therefore, the study of the flame behavior of batteries and how to suppress the flame of batteries is particularly important.

There are many ways to trigger TR, including thermal abuse, mechanical abuse, and electrical abuse [12]. Many scholars have studied battery flame behavior under each of these three scenarios, including flame behavior under mechanical abuse triggered by penetration [13,14], flame behavior under thermal abuse in superheated conditions [15,16], and flame behavior under electrical abuse under overcharged conditions [17]. Regardless of the type of battery fire initiated by the triggering method, the factors affecting the behavior of these flames are similar, and they all exacerbate the TR behavior of the battery to varying degrees. Therefore, it is important to understand the factors affecting the flame behavior of batteries in order to better suppress flames during TR. These factors are categorized into internal and external factors. The internal factors include the battery state of charge (SOC) [18,19], battery healthiness (SOH), etc. [20]. External factors include ambient temperature [21], environmental pressure [22,23], ambient oxygen concentration, etc. [24,25].

According to the factors affecting the flame behavior of batteries, scholars have investigated methods of suppressing battery flames from different perspectives. These methods can be categorized into two directions at a large level: one is active suppression [26,27], and the other is passive suppression [28,29]. Active suppression can achieve the suppression effect more directly compared to passive suppression, but it cannot achieve suppression in the first moment and is more costly. Passive suppression is less costly, but the suppression is not as efficient as that of active cooling. There are considerable papers that mention active flame suppression versus passive flame suppression, but there is a limited overview of them. Therefore, this paper discusses them in detail in the Battery Flame Suppression Section to clarify their relationship more clearly.

The novelty of this work lies in the systematic summary of the behavior of battery flames and the mechanisms that influence flame behavior. Based on these mechanisms, the methods to suppress battery flames are logically summarized. A developmental perspective provides a good idea for future research on battery flame behavior and the suppression of battery flames. In the past, studies on TR process flames have focused on flame behavior. Currently, there are more and more studies on flame behavior affecting TR, both from experimental and simulation perspectives. There are many existing methods for TRP suppression, and a large portion of these studies start from suppressing the flames during TR. Based on practical factors, many scholars have started to study the characteristics of TR flame behavior in confined spaces at the experimental as well as simulation levels. However, there are limited reviews currently that discuss the behavioral mechanisms of battery flames during TR in correspondence with the methods for suppressing battery flames. Hence, this paper provides a comprehensive account of the behavior of flames during TR, as well as the methods to suppress this behavior and the existing challenges through a systematic review of the existing studies.

2. Thermal Safety of Lithium-Ion Batteries

2.1. Flame Disaster of Lithium-Ion Batteries

Whether it is thermal, mechanical, or electrical abuse, TR is triggered whenever a critical condition is reached that triggers TR in LIBs. Prior to TR in LIBs, batteries conform to the following three-dimensional self-ignition model [30]:

$$\rho C_{p,b}\frac{dT}{dt} = Q + \frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial T}{\partial z}\right) \quad (1)$$

where ρ is the cell density, $C_{p,b}$ is the average heat capacity of the cell, T is the temperature of the cell, Q (W/m^3) is the heat generation term as reflected by the side reactions, and k_x, k_y, and k_z are the thermal conductivity of the cell in the x, y, and z axes. And once the battery temperature rises abnormally under abusive conditions, a chain of chemical reactions within it occurs [31], from the collapse of the SEI membrane to the reaction between the electrolyte and the anode; ultimately, the short-circuit inside the battery releases a large amount of heat and flammable gases, causing a flame disaster when the fire triangle is satisfied [12]. This potential flame hazard increases dramatically as the SOC of the battery increases [22]. This is attributed to the fact that the SOC greatly influences the Joule heat released at the moment of TR of the battery, which can be expressed by the following equation [32]:

$$Q_J = \int_0^{t_{end}} I_{ISC,t}^2 R_{ISC,t}\,dt = \int_0^{t_{end}} \frac{U_t^2}{R_{ISC,t}}\,dt \quad (2)$$

where U_t denotes the terminal voltage of the cell, $R_{ISC,t}$ denotes the ISC resistance, and t denotes the end time. The more heat and the more gases that are released from combustion, the greater the flame hazard that can be caused by LIBs. And for the existing popularized packaged battery structure in EVs, once TR occurs, the flame disaster caused by TR in a confined space may be even more serious [10]. Therefore, it is necessary to suppress the flame disaster of lithium batteries.

2.2. The Necessity to Suppress TR Flames

When searching for the keyword "battery fire accident" in Web of science and CNKI, we can find the trend of the number of items in the literature on this topic from 2013 to 2023, as shown in Figure 1. It can be observed that the research trends of Chinese scholars and international scholars are more or less the same. At the international level, the number of articles studying battery fire accidents has risen sharply since 2017. These indirectly reflect the frequent occurrence of battery fire safety problems in recent years. TR-induced battery fires are on a growing trend. This makes it necessary to study the flame behavior during TR in order to explore its mechanism and to suppress TR flames according to the mechanism of battery flames. Therefore, this paper explores the flame mechanism of TR in detail in Section 3 and summarizes the existing methods for suppressing TR flames in detail in Section 4.

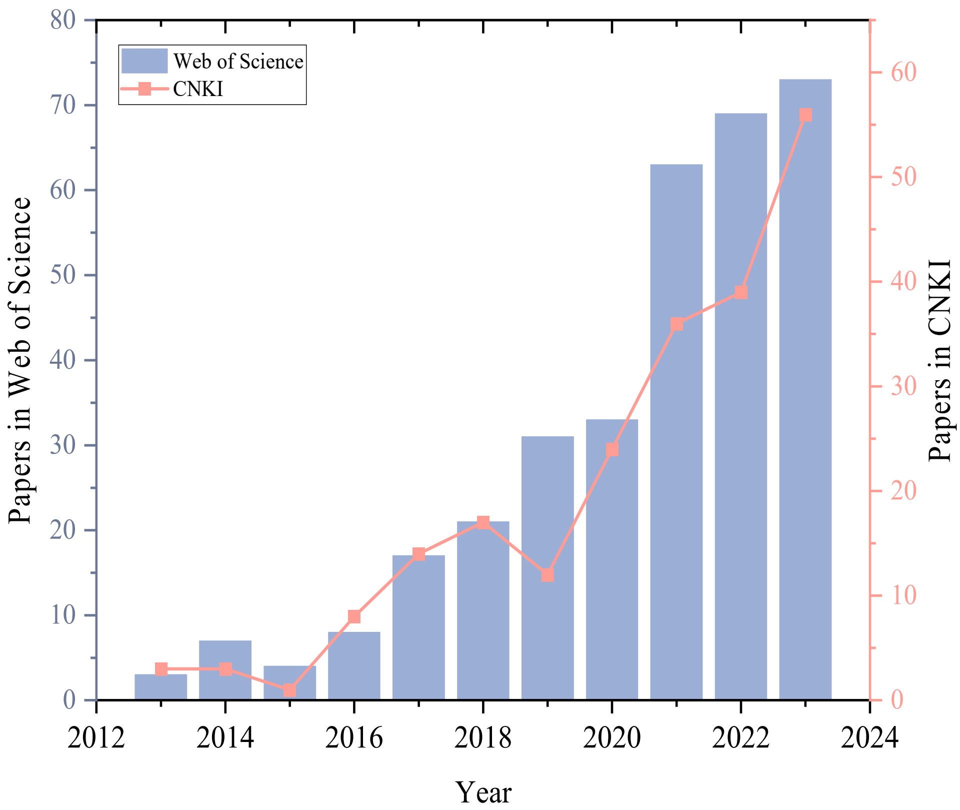

Figure 1. Trend chart of the number of related literature entries in the last ten years.

2.3. Literature Search

The literature search for this review paper followed the PRISMA guidelines and this was conducted to make the paper more scientifically credible. The detailed steps are shown in the Figure 2. The search for this paper was completed in August 2024. The following figure shows the workflow based on the PRISMA 2020 statement. In Web of science, the following phrases were used as a search term: lithium-ion battery, flame, and thermal runaway. Then, the language of the review was limited to English. The search for this review was restricted to 2018 and beyond. The types of articles for the review included research articles and review articles to simplify the review process. The articles were further screened based on their titles, abstracts, and related elements. Sixty-nine articles were finally selected for in-depth analysis.

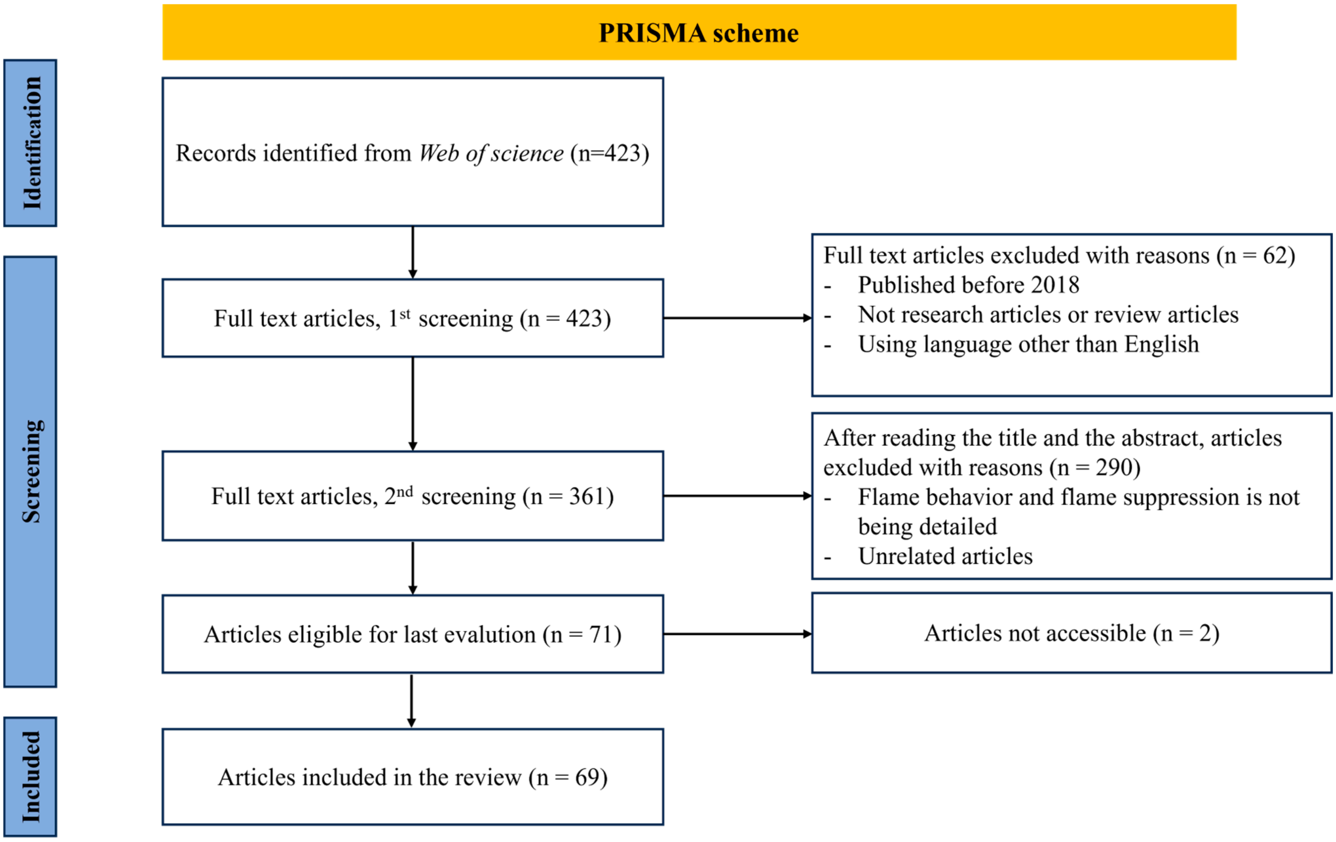

Figure 2. The PRISMA scheme for literature search.

3. Flame Behavior during TR

3.1. Flame Behavior and TR in Single Batteries

3.1.1. TR Progress

There are many scholars who have divided the combustion process of battery TR into several stages in the course of their research. According to Liu et al. [33], the burning behavior is divided into four stages: (I) ignition and venting, (II) steady combustion, (III) jet fire, and (IV) abatement. They found that, for 0% SOC cells, there were no jet flames, and the results are shown in Figure 3a. At stage I, under continuous heating, flammable substances collected in the combustion chamber and were ignited by an external igniter, forming a deflagration fireball. The behavior of fire at stage II was observed by a video camera; after stable combustion, a high-speed jet flame immediately appeared vertically. Subsequently, the flame decayed until extinguishment. Some investigations interpreted the fire behavior in a battery module as a three-stage process: (I) venting/igniting, (II) combustion, and (III) extinguishment [15,34,35]. On the one hand, unlike the above study, they combined steady combustion and jet flame into the combustion module, and, on the other hand, just like in the previous study, they mentioned the influence of the SOC and gas generated from the battery on the behavior of fire in the battery module. And these phenomena are shown in Figure 3b–d. They concluded that, as the SOC rises, the more violent the battery's flame behavior is.

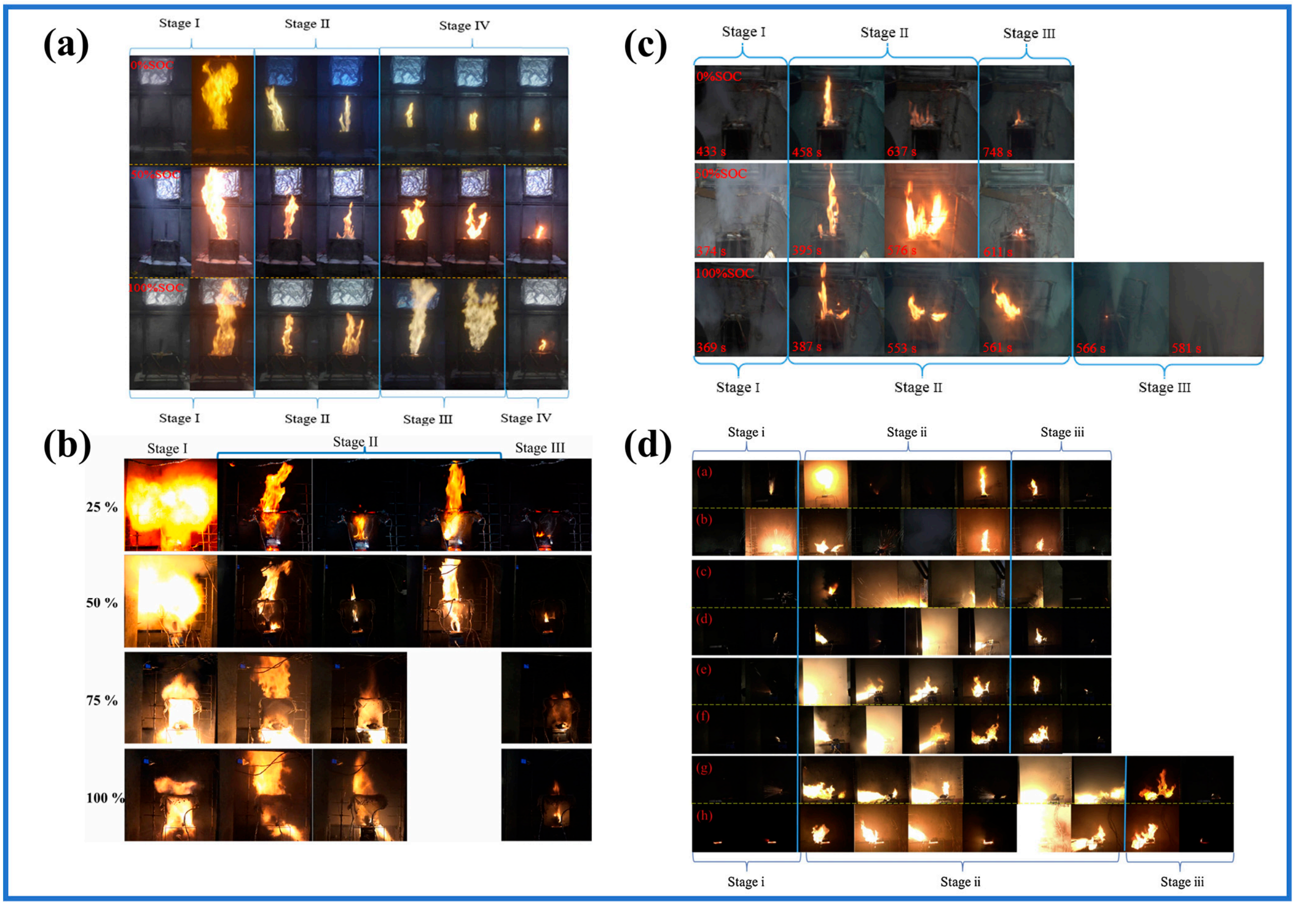

Figure 3. Diagram of phenomena at different stages of TR: (**a**) Burning behavior of LFP LIBs of different SOC [33], (**b**) Flame behavior of NCM pouch cells of different SOC [34], (**c**) Combustion behavior of LFP LIBs of different SOC [15], and (**d**) Combustion behavior of NCM prismatic cells under different heating methods [35].

3.1.2. Influence of Internal Factors

With the increase in the SOC, the mass loss ratio and highest temperature of lithium-ion cells are higher and the time when TR occurs decreased [36]. Wang et al. [34] studied the flame behavior of batteries under external ignition. The results revealed that the trigger time strongly declined with an increase in the SOC. However, there is not a monotonically increasing relationship between the total heat release and SOC. The residual mass of the cell decreases with the increase in the SOC, indicating a very violent ejection of materials, some of which are ignited extremely rapidly. Although the SOC is not relevant to the total heat release, it has an impact on the heat release rate (HRR). According to Chen et al. [22], the HRR is often used to quantify thermal hazards. It was discovered that the SOC of the cell has a significant influence on the peak HRR and the production of CO and HF increase with the increase in the SOC, indicating that the SOC plays an important role in causing thermal hazard. The main reason for this is that, on the one hand, the higher the SOC of the battery, the more reactive its positive and negative electrodes and the lower its thermal stability. Therefore, the lower the trigger temperature of the battery TR, the lower the safety. On the other hand, a high SOC battery releases more energy during TR, which is more destructive to the surrounding environment. Liu et al. [15] investigated TR and the fire behaviors of LIBs induced by overheating, and it was found that, compared to 0% SOC and 50% SOC cells, the jet flow was more violent in 100% SOC battery, which aggravates thermal hazard. According to Zou et al. [37], the thermal ejection duration and flame burning duration of a 38 Ah battery are affected by the incident heat flux and the severity of the TR, both of which increase with the increase in the SOC. Similarly, the ignition time and extinguishing time of a 78 Ah battery also decrease with the increase in the incident heat flux, while the duration of the sustained burning flame remains approximately constant.

Due to many of the gases generated by batteries being flammable, another key risk factor of LIB fire is flammable gas emissions, which are toxic [33]. As the SOC of the battery grows, the battery TR phenomenon advances and even becomes more intensive, and the types of exhaust components released increase, with unsaturated hydrocarbons being the majority of them [38]. As shown in Figure 4a, three types of batteries have been studied; the gases generated from them were H_2, CH_4, C_2H_4, and C_2H_6 [39]. Most components of the gases generated from batteries are flammable [40], which are beneficial to the behavior of jet fire, and the main components of thermally induced runaway gas in LIBs are not influenced by the SOC [41]. The details are shown in Figure 4b. Although there is little difference in the main components, the concentration of each gas increases significantly with the increase in the SOC, especially CO and H_2, which poses a potential risk of fire and explosion in the battery system [41]. Wang et al. [42] investigated the gas production behavior and flame behavior of 50% SOC and 100% SOC LIBs when TR occurred. It was found that, under the conditions of gas production and flame, the maximum temperature of the 100% SOC battery was much higher than that of the 50% SOC battery. What is more, as the gas was ignited, the accumulation of large quantities of gas will cause a risk of toxicity and explosion. The gas temperature, concentration, and typical components are shown in Figure 4c. It is apparent from the information supplied that the battery's SOC has a considerable influence on the generation of gases, and both flammable gases and the SOC are relevant to the behavior of flames.

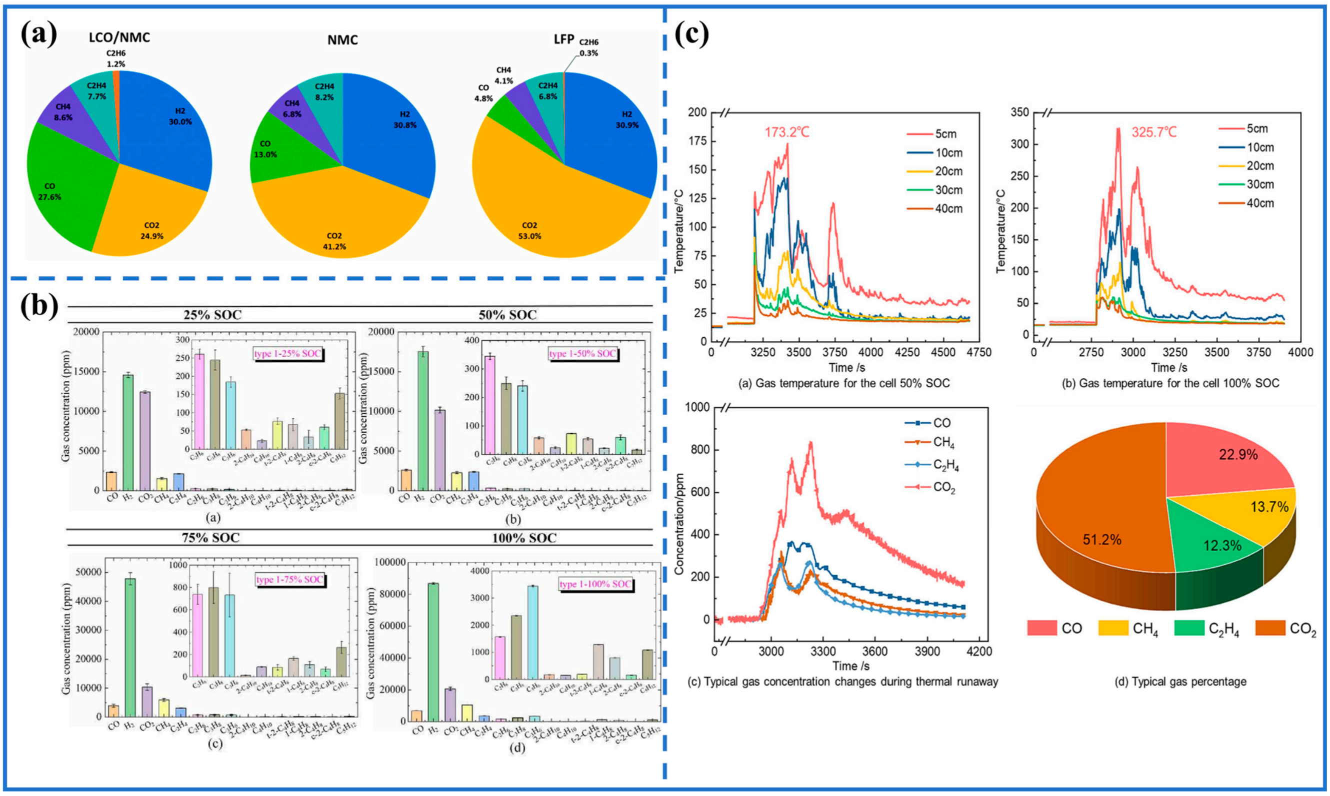

Figure 4. (**a**) Composition of gases from three different batteries [39]. (**b**) Main components of thermally induced runaway gas in LIBs with different SOCs [41]. (**c**) Gas temperature of different SOC LIBs and the concentration and typical components of a battery's gas [42].

In addition to the impact of the battery capacity on the gas produced during TR of the battery, the health of the battery also has an impact on it, which indirectly affects the flame behavior of the battery during TR. Some studies had shown that higher SOC and SOH cause more intensive reactions with a greater gas release and heat energy [43,44]. Liu et al. [20]

studied the factors that have an impact on LIBs in a confined space, and they found that the cumulative exothermic side reactions increased with the decrease in SOH, and that a lower SOH increased the risk of danger in LIBs to a certain extent, because batteries with lower SOH values were more prone to fire accidents. Wu et al. [45] explained the reason for this phenomenon in more detail, because at the same temperature, the self-heating rate of aging batteries is higher, which shows that the lithium deposited on the anode during low-temperature aging will greatly reduce the thermal stability of LIBs. The following three chemical Equations (3)–(5) [46] are the reaction of lithium metal with the electrolyte to produce gas, which corresponds to the peak of the reaction when the battery bursts. The difference in cell self-heating rate is most pronounced at this time for different battery health values, which explains why batteries with a low battery health exhibit lower rupture temperatures.

$$2Li + C_3H_4O_3(EC) \rightarrow LiCO_3 + C_2H_4 \tag{3}$$

$$2Li + C_4H_6O_3(PC) \rightarrow LiCO_3 + C_3H_6 \tag{4}$$

$$2Li + C_3H_6O_3(DMC) \rightarrow LiCO_3 + C_2H_6 \tag{5}$$

During the TR of a battery, the battery produces gases as well as some fumes, which are not only harmful to the human body [47], but also have an impact on the flame behavior of the battery [48,49]. It is worth noting that the influence of flue gas on the flame during the TR of the battery has not been paid attention to until recently; so, the current research in this aspect is relatively limited, especially to experimental study.

Wang et al. [50] studied the TR hazard of LIBs, and details are shown in Figure 5. The own hazardous factor of the battery (B1) is mainly concerned with its own dangerous state when the battery experiences TR. B2 included the factor of vented gases, which were characterized by their explosion hazard, toxicity, and pressure. B3 was jet fire and high temperature, and B4 consisted of ejected powder. According to Liu et al. [51], the results were the fact that the charging rate, ambient temperature, and battery aging have an influence on TR, and the conclusion of the orthogonal tests indicated that the rank of the influence on the thermal runaway risk was charging rate > ambient temperature > aging. It is apparent that, except for the charging rate and ambient temperature, all of the factors mentioned above are produced from an internal cause, which have an impact on TR and fire behaviors at some scale. As a matter of fact, there are some external factors of the environment that have an influence on flame behavior as well.

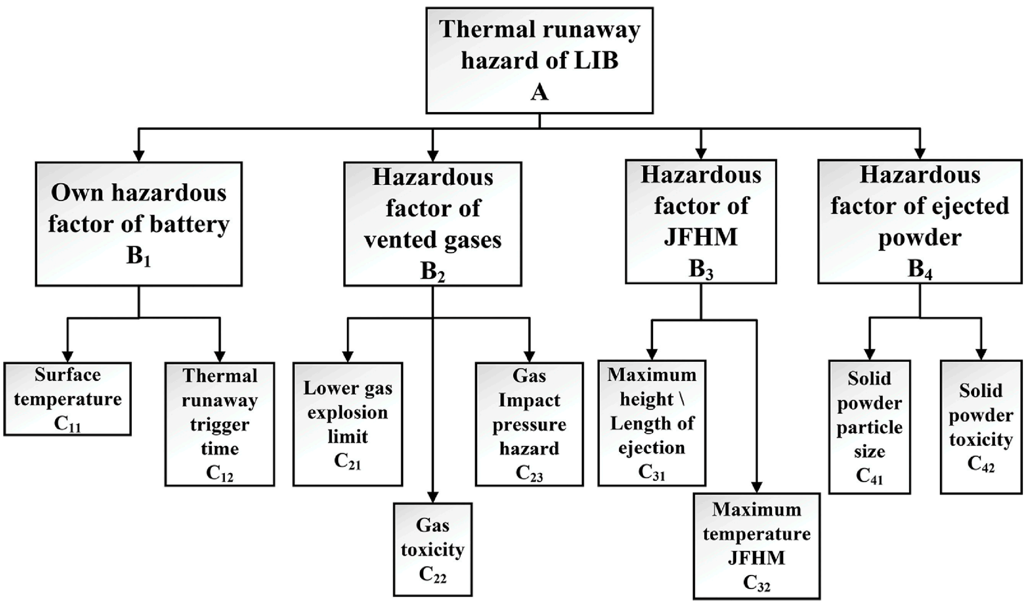

Figure 5. Hierarchical index system for the multi-parameter assessment of TR in lithium-ion batteries [50].

3.1.3. Impact of External Factors

Previous studies have shown that TR and the battery's flame behavior are related to the concentration of oxygen [52–54], and the flame is almost not able to exist under 12 precent oxygen concentration for common hydrogen fuel gases [55,56]. What is more, inert gas dilution has a profound effect on the flame propagation and extinction [57], the reason for which being that inert gases can lower the oxygen concentration to smother the flame [58]. Weng et al. [24] investigated the effects of the oxygen level and dilution gas on alleviating on battery TRP. By mainly measuring the temperature of jet fires of different heights and observing the flame duration, it is obvious that lowering the oxygen concentration can weaken the flame behavior when TR occurs, and details are shown in Figure 6a. Additionally, by comparing different inert gases, the results showed that both argon and nitrogen dilution can slow down TRP, one essential reason for which being that decreasing the oxygen concentration through extra inert gas dilution can reduce the value of the flame heating (q_f) and total heating (q_t), indicating that the fire behavior was also suppressed because of the inert gases. The above conclusions were also verified in an experiment that better reflects the characteristics of the battery module. According to Yan et al. [59], it has been found that a completely confined space suppresses the maximum temperature of the battery due to the insufficient combustion of the gases emitted from the battery. Therefore, reducing the amount of oxygen in the battery module may be beneficial in preventing TRP. The central reason for the diminished flame behavior of the battery described above is that the oxygen in the battery's burning fire triangle is weakened. There are current studies on how the oxygen concentration affects the flame behavior and how inert gases can be used to suppress TRP. In the future, methods for suppressing cell flames by attenuating the oxygen concentration need to be further refined. How to make the operation easier and to improve the environmental friendliness of the method are current issues that need to be addressed.

Except for the impact of the battery' SOC and ambient concentration of oxygen, the environment's pressure also has influence on the flame behavior of the battery [60]. Chen et al. [22] found that the ambient pressure has a significant effect on the heat of combustion, and the (total heat release) THR value at a high pressure is relatively larger than that at a low pressure. Also, the unit growth rate of the heat of combustion at both pressures increases with the increase in the SOC. The mechanism is depicted in Figure 6b, where a simplified diagram of the pressure by competition between the internal pressure and environmental pressure and the crack pressure is defined as: $P_{crack} = P_{in} - P_{out}$. What is more, the difference in the relief crack pressure also has an effect on the combustion behavior of LIBs. Wang et al. [61] found that, as the ambient pressure decreases, the TR trigger time becomes longer and the maximum surface temperature decreases. Ding et al. [23] investigated the environmental pressure effects on the TR properties of 21,700 LIBs with high energy density, and they found that the pressure had an impact on the height of the jet flame, which reached the maximum at 50 kPa. Nowadays, there are many studies on the effect of the pressure on the flame behavior of the battery TR, while studies on suppressing the flame behavior of the battery in this regard are limited. Some scholars have studied the effect of different safety valve types on battery disasters. And the application of a safety valve is closely related to the environmental pressure around the battery. Therefore, in the future, it is important to analyze the design of safety valves in combination with the environmental pressure where the battery is located. The study of a safer safety valve is very promising for the reduction in battery flame disasters.

According to Wang et al. [62], the combustion and explosion of outgassing in the event of a battery failure can be catastrophic for an electrochemical energy storage system. The fire hazard posed by outgassing from lithium iron phosphate batteries is greater than that from NCM batteries. The spray intensity at 30 kPa is significantly stronger than that at 95 kPa due to the higher pressure difference at which the combustible material is released [63]. Wang et al. [64] also studied the TR behavior of lithium-ion phosphate batteries. And they studied the effect of the charging rate on the battery exhaust behavior, which in turn affected the flame behavior of the battery during TR. They divided the TR behavior of lithium-ion phosphate batteries overcharged at different rates into the following stages: electrolyte vapor discharge, jet ignition, stable combustion, attenuated combustion, secondary injection, combustion and smoke, and gradual extinguishment. The results showed that the high-rate battery exhibited a more severe ignition and ejection than the low-rate one (0.5 C), not only evolving faster, but also appearing twice. At 0.5 C, the electrolyte vapor injection is more violent, which may be due to the prolonged accumulation of internal gases generated after a long period of charging. Some relevant details are shown in Figure 6c. Also, under charging conditions, Meng et al. [21] studied the effect of the ambient temperature on TR during the charging of LIBs, and the results showed that the battery exhibited greater thermal hazards at high charging rates and high ambient temperatures. Talele et al. [65] came to a similar conclusion through numerical simulations; the higher the temperature, the shorter the time the battery took from being heated to TR, as shown in Figure 6d.

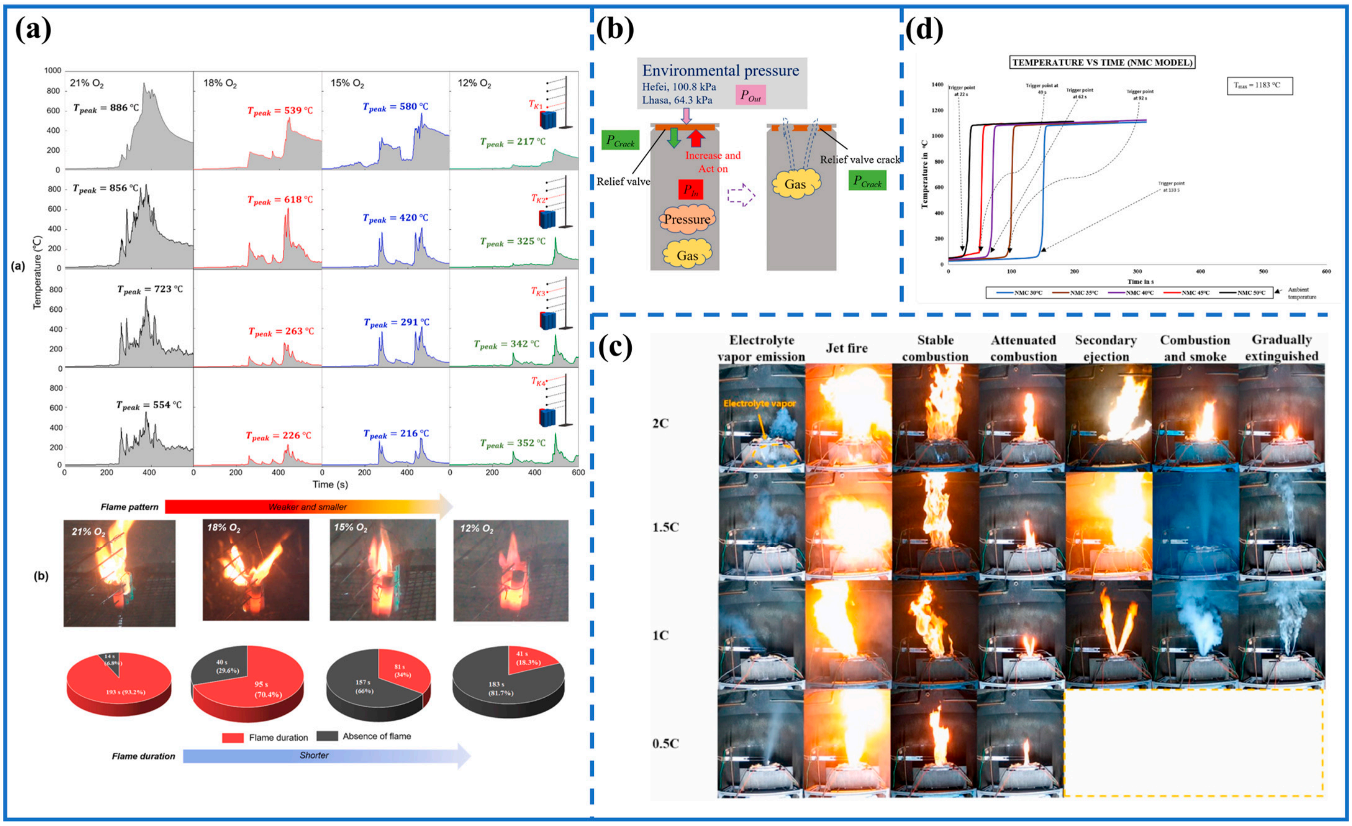

Figure 6. (**a**) Temperature of the battery module and flame pattern at different oxygen concentrations [24]. (**b**) Schematic representation of the effect of the ambient pressure on a battery [22]. (**c**) TR evolution under overcharge at different rates [64]. (**d**) Electrochemical model TR trigger point at different ambient temperatures [65].

To conclude, when TR occurs in batteries, the battery flame behavior caused by it is influenced by many elements, which consist of two large scales: external factors and internal factors, including battery health, state of charge, gas and particles, ambient temperature, charging rate, ambient concentration of oxygen, and environment pressure. It is obvious that, when a battery undergoes TR, the jet fire becomes a more and more important factor worthy of study, which can be influenced by plenty of factors. The jet flame is a special behavior when a battery TR occurs, and it causes great harm to surrounding objects [66–68]. And ambient batteries are inevitably influenced by it; as a consequence, the flame behavior in the battery module is even more worthy of study.

3.2. Discussion of Flame Behavior and Hazards for Different Types of Batteries

Because the flame characteristics of batteries are more related to the type of battery and its components, this work provides a systematic categorization and summary of some of the articles reviewed. The aim is to clarify the influence of the shape of the battery and its components on the flame behavior of the battery. An in-depth discussion on the hazards of the different components of the battery was carried out. The flame evolution of different types of batteries during TR is summarized in Table 1.

Table 1. Summary of the flame behavior of LIBs of different types.

Type	Materials	Trigger Mode	Flame Pattern	Refs.
Cylindrical LIBs	LFP/graphite	Overheat	Venting, sparks, combustion	[22,41]
	LFP/graphite	Penetration	Venting	[43]
	LCO/graphite	Overheat	Venting, sparks, combustion	[22,60]
	NCM/graphite	Penetration	Venting, sparks, combustion	[13,14]
Prismatic LIBs	LFP/graphite	Overheat	Venting, jet fire	[33,42]
	LFP/carbon	Overheat	Venting, jet fire	[15]
	LFP/graphite	Overcharge	Venting, jet fire	[17]
	NCM/graphite	Overheat	Venting, jet fire	[35,37]
Pouch	NCM/graphite	Overheat	Venting, jet fire	[34,69]
	NCM/graphite	Penetration	Venting, combustion	[70]
	LFP/graphite	Penetration	No combustion	[70]
	LCO/graphite	Penetration	Venting, combustion	[70]

It is easy to see from the table above that, when a battery undergoes TR, it almost always has the process of ejecting combustible material out of it. The way the battery is packaged has a greater impact on its flame behavior than the way it triggers the battery TR. Cylindrical batteries mostly have a sparking link. In contrast, pouch and prismatic batteries have more space to cushion because the pressure is mainly concentrated in the upper part of the battery when it undergoes TR. Thus, most of these two types of batteries will have a jet flame during TR. By analyzing these articles above, we can see that the way TR is triggered also has some effect on the behavior of the battery flame. Generally speaking, the flame behavior of TR triggered by mechanical abuse and electrical abuse will be more intense than that by thermal abuse. This is because the first two interact directly with the internal components of the battery, which tends to result in a more violent reaction within the battery, leading to a greater release of energy. For the battery components, the results of the study show that LCO > NCM > LFP in terms of the potential hazard of TR [70]. For LFP batteries, especially for mechanical abuse as a means of triggering TR, the risk is minimized. Therefore, in the future, it will be important to use the right type of battery for the right occasion.

3.3. Flame Behavior and TPR in Battery Module

The battery module tends to experience TR when suffering different abusive conditions [8,71], which always lead to fire and explosion accidents. There are three types of abuse causing TR, which include mechanical abuse, electrical abuse, and thermal abuse; all of them will probably lead to TRP at certain circumstances [72]. Song et al. [73] investigated TRP behavior and energy flow distribution analysis of a 280 Ah $LiFePO_4$ battery. They found that the heat from a single cell had influence on the TRP and a considerable fire hazard at a large scale.

In fact, there are plenty of factors that have an impact on the behavior of TRP occurring in the battery module, and many studies about this have been conducted. Mishra et al. [74] investigated the TRP during the large-scale storage and transportation of LIBs, and the propagation of TR from one pallet of cells to an adjacent pallet was studied. They found that the gap between pallets plays a key role in determining the propagation. Using a cylindrical 18650 LIB, Wang et al. [75] identified and characterized the factors that lead to TRP in a battery module. The results show that cyclic aging has little effect on the propagation process and is more likely to lead to TRP in a battery module when the positive terminals are placed in the same direction than when the positive and negative terminals are placed in the same direction. Meanwhile, a parallel connection increases the probability of TRP. The main reason for this phenomenon is that the parallel connection exacerbates the exothermic reactions within the cells, leading to more violent combustion and energy release from the parallel cells. This results in a higher heat flux from the cell with TR to its neighboring cells, thus accelerating the TRP. Zhou et al. [76] experimentally investigated the TR characteristics and the corresponding triggering mechanism of parallel prismatic cells. It was found that, compared to the open circuit, the TR of the parallel cell is triggered in advance by the electrical energy transfer generated by the local ISC. In contrast, for an open circuit, the localized TR is always triggered first in the heated zone with a higher temperature and then propagates to the whole battery module. Jin et al. [77] investigated the effects of heating power and heating energy on the TRP characteristics of battery modules through both experiments and simulation. What they discovered is that the heating power had a slight influence on the TRP in the battery module and, most importantly, the mechanism of TR triggered by external heating was revealed: the accumulation of heat energy. In many circumstances, the jet fire produced by the battery when TR occurs is a vital factor that leads to the accumulation of heat energy. For instance, Wang et al. [78] studied the propagation characteristics of TR. They used a 670 W heater to trigger the TRP of LIBs and recorded the flame behavior of a battery: Initially, the flame was sprayed on both sides; then, the flame appeared in the form of a jet flame with pressure, and finally entered a state of stable combustion. The flame behavior of four batteries is shown in Figure 7a(1a–4d). In the process of TRP, the flame has a significant effect on the temperature around the battery and vents, reaching about 500 °C, as shown in Figure 7a(e,f). Zhu et al. [69] found that the change in the SOC has a greater impact on TR flame ejection behavior than spacing between cells. And as depicted in Figure 7b, the mechanism of TRP in the NCM battery module was revealed: when there is no spacing between cells, the heat transfer between the neighboring cells is mainly through heat conduction and thermal radiation from the flame; when there is spacing between cells, the heat transfer between neighboring cells is mainly through thermal radiation, which indicates that the jet flame plays an important role in TRP. Zhang et al. [11] studied the effect of flame on the TRP of the battery module by changing the height of the roof plate and the heating mode of the heating plate. And they used the time interval of the TRP to reflect the effect of the flame on the battery and changed the radiation amount of the flame on the battery pack by adjusting the height of the roof plate. As shown in Figure 7c, with the decrease in height, some batteries that do not have TR at higher altitudes experienced TR, and the lower the altitude, the more obvious the effect of the flame on the battery and the shorter the time interval of TRP. In the meantime, the harm of continuous heating is greater than that of non-continuous heating. What is more, in an actual battery module, as mentioned by Zhang et al., the jet fire will spread and transfer considerable heat to other cells when impacting the wall surface, as a consequence of which the promoting effect will be further enhanced. Therefore, more and more studies about fire's impact on TRP have emerged. Huang et al. [66] conducted an experiment about the thermal and combustion characteristics of flame propagation over a large format battery module and they discovered that flame heating had considerable effects on TRP. Said et al. [52,79] analyzed the dynamics and hazards associated with cascading failure in 18650 lithium-ion cell arrays, and it was found that, compared to nitrogen condition, the propagation speed in air was quicker, which indicated that jet fire accelerates the TR behavior of adjacent cells. Especially, the convective heat transfer by VOC and H_2 combustion played an important role in TRP [80].

Through the above analysis, we can find that the behavior of the flame plays a more or less accelerating role for TRP in the battery module. Suppressing the heat buildup to the surrounding cells is the key to suppressing TRP. For this purpose, we can use heat dissipation materials to dissipate heat and reduce the rate of heat buildup, such as PCM and other materials. We can also use thermal insulation materials to insulate and block the spread of heat to the surrounding cells, such as materials like aerogel felt. Suppressing the absorption of flame radiation with qualified radiation protection materials is also an idea to effectively suppress TRP. How these methods can be better synthesized and applied in practice in the future is something that requires further research.

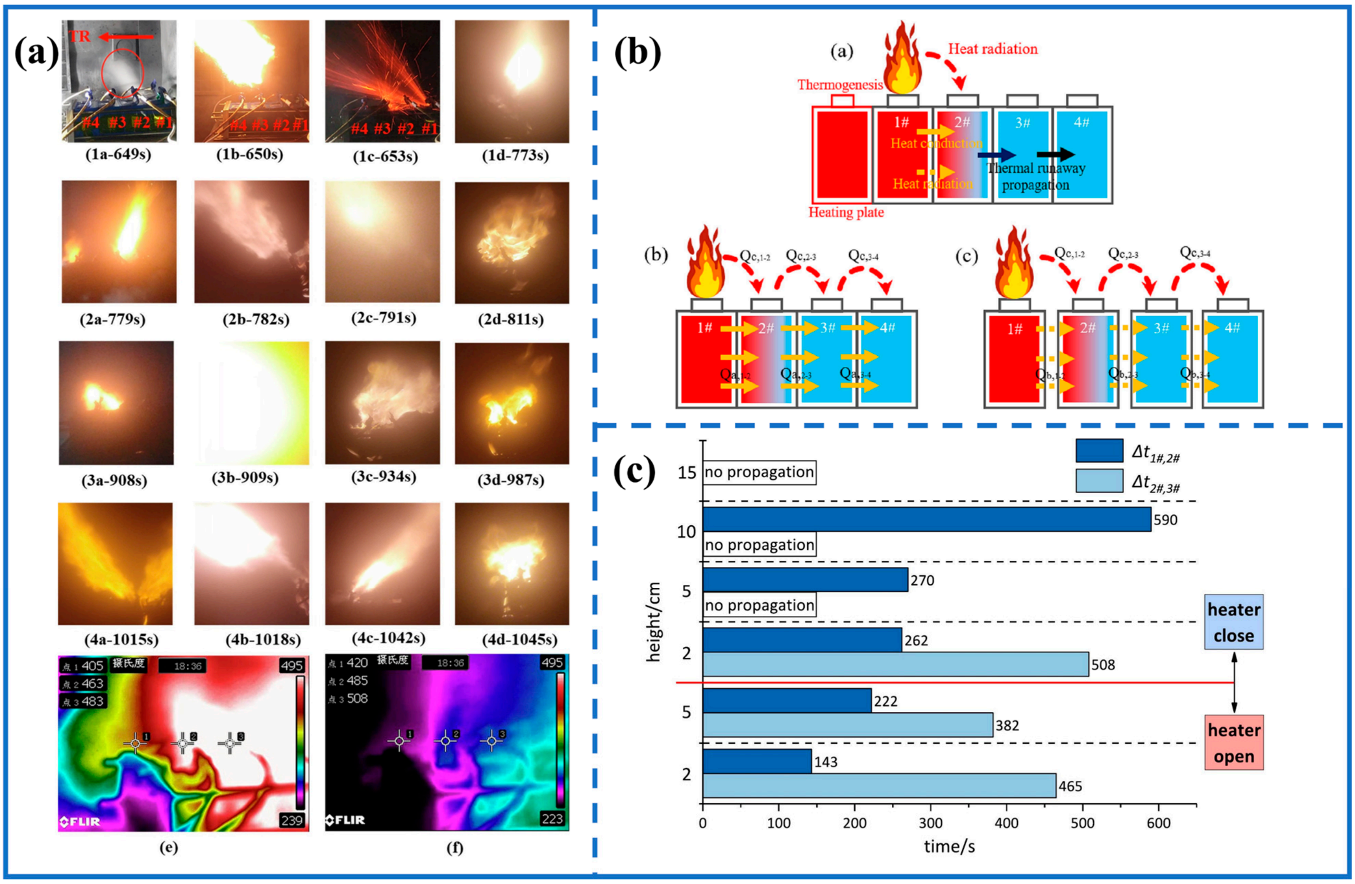

Figure 7. (**a**) The flame behavior of NCM battery and its thermal image during TRP [78]. (**b**) Two main ways of TRP path in NCM battey module: heat conduction and heat radiation [69]. (**c**) The TRP time between adjacent batteries for all experimental conditions [11].

3.4. Flame Behavior and TPR in Confined Space

3.4.1. Difference between CS and OS

The combustion performance of cells in a confined space is very different from that in open space [7,59], and so it does in the behavior of TRP. According to Wang et al. [81], when TR occurred in a confined space, combustible gases were ejected and then spread to the upper surfaces of neighboring cells, blocked by the ceiling. The spread of the ejected fire enlarged the heat transfer area and enhanced the radiative and convective heat flux between the cell and the fire. At the same time, the total amount of combustible gases was greater in a confined space than in open space. Therefore, it possesses larger potential deflagration risks, which will cause the speed of TR to be accelerated. Zhang et al. [82] investigated the effect of a plate obstacle on the flame behavior of 18,650 LIBs, and the phenomenon of the different performance of TR in a confined space and open space was described. Comparing the heat flux in a confined space (CS) and open space (OS), it was found that the radiation heat from the flame was affected by the plate obstacle with larger values, and the maximum heat flux was about four times that of OS. As shown in Figure 8b, the maximum length of the fireball before the formation of the jet flame at different plate heights is different from the case of OS, where the fireball length is larger for heights up to 10 cm and increases linearly with the decrease in height. This phenomenon may lead to more serious consequences of TR, such as a stronger thermal radiation to the surrounding area. What is more, as depicted in Figure 8a, with the decrease in the height of obstacle, the radiant heat flux rose more and more rapidly than that of OS, illustrating the difference between OS and CS. Liu et al. [83] compared the TRP interval, battery voltage, and the maximum temperature of the environment in a confined space and open space during the TRP period of batteries, and found that the confined space has a great influence on the ambient temperature, and the maximum temperature of environment in a confined space is much higher than that in open space, as shown in Figure 8c. Due to space constraints, the high ambient temperature and flame radiation accelerate the TRP between battery modules. This phenomenon can be more intuitively reflected in the energy storage station. For instance, Wang et al. [84] studied the propagation of the battery flame in the energy storage station in the half-reduced order model of the multi-scale simulation of battery fire propagation in the energy storage system. What they found was that the fire spread upward rapidly after the gases were released from the battery modules. The upward flame almost impacted all the upper battery module, which promoted the upward TRP by heating the packs' side surfaces through thermal convection and radiation.

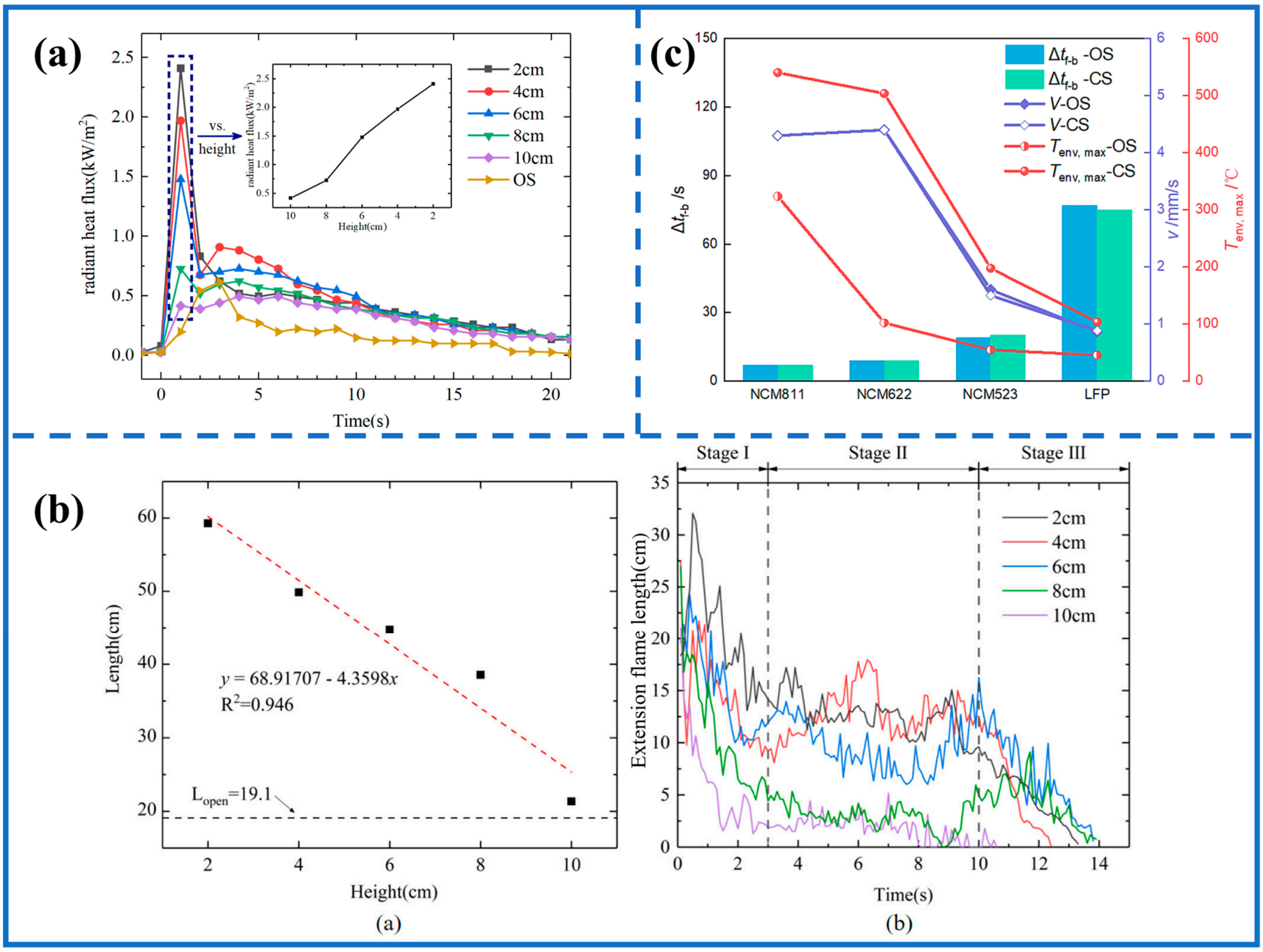

Figure 8. (**a**) Heat flux in a confined space at different heights and in an open space [82]. (**b**) The length of fire balls and extension flame at the plate at various plate heights for 18650 cylindrical NCA batteries [82]. (**c**) The maximum temperature and TRP time in a confined space and open space [83].

3.4.2. Flame Function

In a confined space, a large amount of heat is generated by the flame, which directly makes the TR behavior more severe, and the HRR is significant in quantitatively evaluating the flame development process and subsequent flame intensity [83]. The flame's behavior in a confined space has been widely studied in other fields. For instance, You et al. [85] conducted an experiment about the heat transfer characteristics of turbulent plumes and fire behavior on a horizontal ceiling, and it was found that, as the degree of confinement grew, the heat fluxes around the confined space tended to increase. Zhang et al. [86] used a three-regime lay to interpret the change in the maximum temperature at the impingement zone. What is more, the term "effective ceiling HRR" was defined to characterize the confined ceiling jet properties, by which the ceiling flame length was physically correlated [87]. According to Wang et al. [88], a systematic investigation on the vertical plate impinged by horizontal jet fires was conducted, and the flame extension area as well as the temperature profile in the thermal impinging flow were studied. Additionally, their corresponding correlations were proposed. All investigations mentioned above are important to understand the mechanism of flames on the TR behavior of batteries in a confined space. Zhang et al. [11] investigated the effect of flame heating on the TRP of LIBs in a confined space, as depicted in Table 2. The TRP of the battery module mainly contributed to the ceiling flame in a confined space and the influence of the flame increased as the height decreased, indicating the energy from the flame was the most dominant heat source to trigger the TRP in a confined space.

Table 2. The proportion of heat to trigger TR during combustion [11].

Heating Mode	Height (cm)	$Q_{transfer}$	Q_{tr}	Q_{flame}
Non-continuous heating	2	2.7%	22.1%	75.2%
	5	5.2%	20.2%	74.7%
	10	29.4%	17.1%	53.5%
	15	/	/	/
Continuous heating	2	3.7%	20.6%	75.7%
	5	16.5%	17.4%	66.1%

As shown in Figure 9a, compared to the situation of an open space, which did not have a ceiling plate, the smoke temperature in a confined space was higher, and with the growth in the SOC, the temperature increased [8]. When it comes to the angle of the plate in a confined space, the results indicated the TRP only happened at a lower ceiling angle and the horizontal ceiling structure was the most dangerous. And some details are shown in Figure 9b,c [89]. To conclude, in a confined space, the ceiling plate blocks the flame emitted from the combustion zone, which makes the flame play an important role in the TPR of batteries in a confined space. Obviously, in a confined space, the height of the plate is an essential factor that cannot be neglected; the height of the roof affects the tightness of the confined space to a certain extent and also affects the behavior of the flame. For instance, with the decline in the height of the plate, the flame heating power to batteries 2 and 3 grew. What is more, no matter whether the heater was opened or closed, the TRP time was shorter. Some relevant details are shown in Figure 9d,e [11]. In essence, it is because the radiant heat flux increases greatly as the height decreases [82].

At this stage, the study of flame behavior during the TR of batteries in a confined space is relatively rare, especially for fully enclosed battery spaces. The difficulty lies in the fact that the experimental process is more difficult to observe and the experiment is more difficult to operate. How to suppress TRP in a confined space is a focus of the research needed nowadays, and the current research on this is very limited. In the future, we can combine simulation and experiment more often to verify the experimental results while reducing the complexity of operation. Meanwhile, the rise in AI technology also provides a new direction for predicting the flame behavior during the TRP of batteries in a confined space in the future.

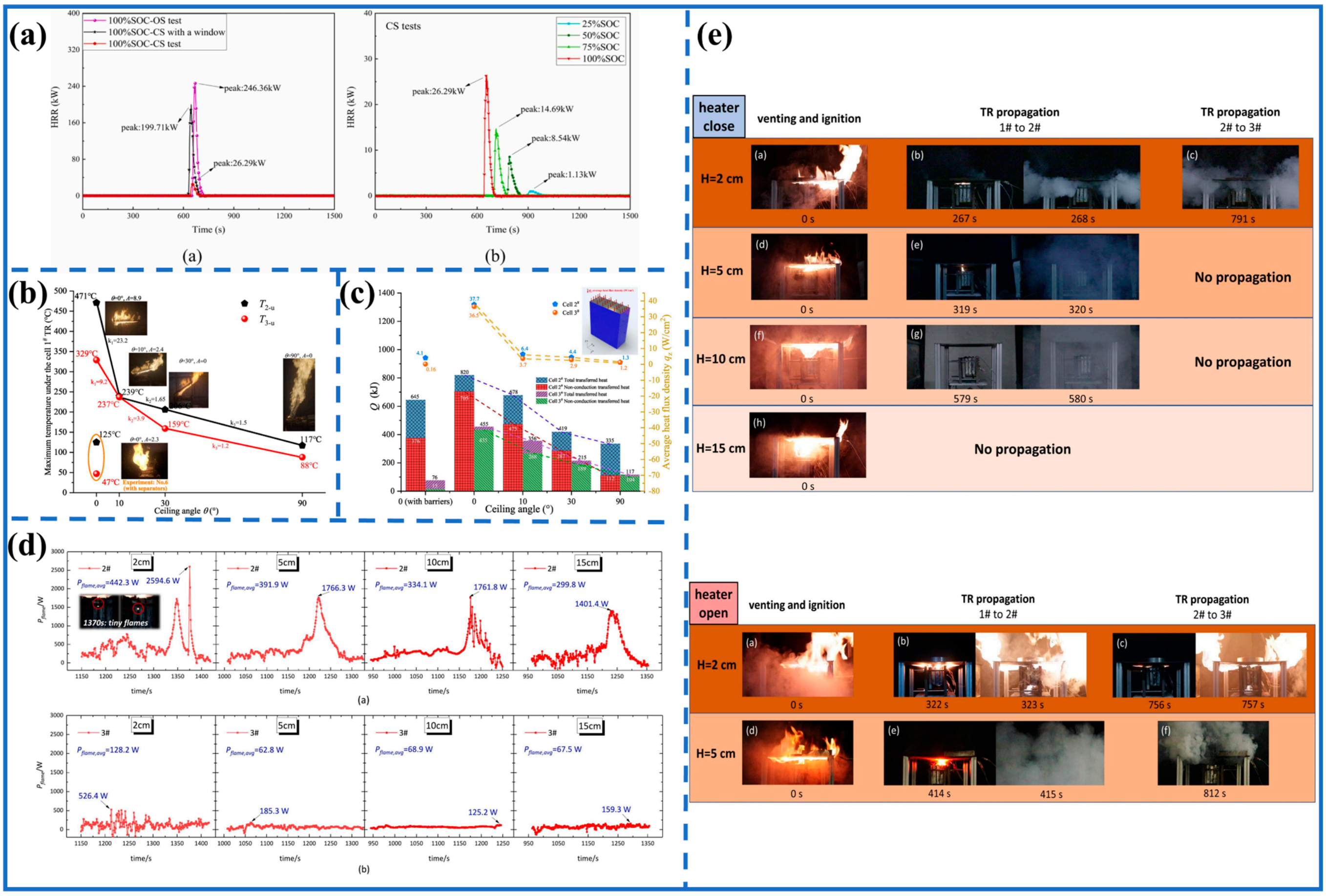

Figure 9. (**a**) HRR variations in cells under open space and confined space; HRR variations for cells of different SOC in confined space [8]. (**b**) Maximum temperature of the cells' upper surface for different ceiling angles [89]. (**c**) The average heat flux density in the z direction for different ceiling angles [89]. (**d**) Flame heating power to batteries at different plate heights in confined space [11]. (**e**) The evolution of the TR behavior for the battery module with non-continuous heating and continuous heating [11].

3.5. Relevant Flame Modeling

3.5.1. Development of Flame Modeling

A number of models of the TR behavior can be found in many papers. Firstly, Dahn et al. [90] formulated a mathematical model on the basis of the SEI layer and the decomposition rates of the anode. Later, Hatchard et al. [91] investigated the oven exposure testing of a standard benchmark and developed an one-dimensional predicting model for it. The main aim of this article was to predict the response of a new battery. Considering Hatchard did not illustrate abuse behaviors, Kim et al. [92] used Fluent to developed a three-dimensional model on the basis of Hatchard's model. All models introduced above have a lack of venting and electrolyte vaporization, as a consequence of which they obviously cannot predict the exact TR behavior. To improve the accuracy of the model, Coman et al. [93] built a lumped model with a series of ODES representing the decomposition rates, the energy balance, and the ideal gas flow equations. The model showed a good agreement when compared in terms of the temperature and vented gas tendencies. Almost at the same time, paying attention to the battery itself, Feng et al. [94] built a 3D TRP model to find solutions for the prevention of TRP and the simulation they used was the same as that of Comen. Not long after that, Coman et al. [95] improved their model to predict the temperature–pressure behavior and gas generation in 18,650 Graphite/LCO cells. In this study, they firstly illustrated the jet flow dynamics by isentropic flow equations. Bugryniec et al. [96] also used COMSOL to build an advanced abuse model. Due to its improved temperature predictions, it considerably enhanced the LIB TR field of study. Other scholars used computational fluid dynamics (CFD) techniques, which overcame the limitations of the lumped model to provide flow field evolution and distribution [97], and many people used it to establish fire modeling in the field of battery.

According to Kong et al. [98], they developed a numerical model, which combined the thermal decomposition reactions, pressure build-up and venting mechanisms, and combustion process. By coupling conjugate heat transfer with CFD to capture the cell temperature and internal pressure evolution under thermal abuse, they indicated that the radiative heat loss from solid particles and soot was neglected in their model, as a consequence of which it possibly caused 20–40 percent overprediction in jet flame temperatures. To predict the hazards to a wider environment induced by the heat and gas release of the battery flame, one model used the CFD simulation of a battery fire test, which was based on the three main heat-generating TR mechanisms [99]. However, the transport of the ejected particles was not considered in any of the above models, and few studies have considered the effects of solid particle radiation in a prediction model of TRP [49,97]. Based on the above-mentioned situation, some scholars have studied the influence of the particles generated during the TR of the battery on the TR behavior and the influence of the battery flame by establishing the corresponding model on the basis of previous studies.

To solve the problems above, Wang et al. [97] investigated how particles are generated and how particles and gases interact in their new model. They successfully simulated the particles' ejection process during TR; however, their model lacked a combustion process. Aiming to fill this gap, a model integrating the effects of the conduction, convection, and radiation of particles was established by Zhang et al. [49]. This multi-physics model based on ANSYS Fluent can be used to predict the TR process, which included many reactions. Not long after that, as the effect of solid particles on the jet flame generated during TR had not been thoroughly studied, Wang et al. [48] used the discrete particle model (DPM) to calculate particle–fluid coupling. And they demonstrated that the particles had a significant impact on the jet flame characteristics and dynamic behavior during TR with their model. The development of battery fire modeling is as shown in Table 3.

Table 3. The development of battery fire modeling.

Year	Aim	Methods	Simulations	Highlights	Ref.
1999	Calculate self-heating rate profiles	ARC	Mathematical model	A mathematical model was used to study the thermal stability	Dahn [90]
2001	Predict the response of a new battery	ARC Fortran	One-dimensional predictive model	A one-dimensional predictive model was established	Hatchard [91]
2007	Illustrate abuse behaviors	Fluent	Thermal–fluid dynamics	A three-dimensional thermal abuse model was established	Kim [92]
2016	Analyze thermal runaway during venting	Comsol	Mathematical and multi-physics model	Flow equations were used to better understand thermal runaway	Coman [93]
2016	Find solutions for preventing TPR	Comsol	Mathematical and multi-physics model	A 3D TPR model for a battery pack was built	Feng [94]
2017	Predict the temperature–pressure behavior in battery packs	Comsol	Mathematical and multi-physics model	The pressure inside the battery was predicted	Coman [95]
2020	Investigate cell pressurization and abuse reaction of LIBS	Comsol	AAM (advanced abuse model)	Capable of predicting pressure accumulation	Bugryniec [96]
2022	Predict the thermal abuse reactions and jet dynamics	CFD	A coupled numerical model	Combined many sub-models that are necessary for prediction	Kong [98]
2022	Predict the hazards induced by heat and gas release of battery fire	CFD	Thermal–fluid dynamics	It can determine the release of heat and gases from the battery	Voigt [99]
2022	Simulate the particle ejection process	CFD	Multi-scale and multiphase modeling framework	The complete evolution of the ejected particles was simulated	Wang [97]
2023	Analyze the effect of particles' radiation	CFD	A coupled numerical model	Combined the effect of particle radiation into TR innovatively	Zhang [49]
2023	Analyze the influence of particles on the jet flame	CFD	A coupled numerical model	The connection of the particles and characteristics of the jet flame was revealed	Wang [48]

It is not difficult to see from the above that, with the passage of time, the model was developed from the simplest one-dimensional model to the current multi-scale and multi-stage modeling framework. And the goals achieved by the model are becoming more and more accurate, and the tools are gradually refined. In the field of fluids, the CFD module in COMSOL is very popular. Especially in the study of battery flame behavior, CFD is the most used, because CFD is especially suitable for the fluid field.

3.5.2. Flame Modeling in a Confined Space

At this stage, the simulation of batteries in a confined space is still relatively scarce. In the research of battery TR simulation, initially, people only focused on the TR itself inside the battery. Subsequently, the gas emission during the TR of the battery and the influence of the subsequent combustion behavior on the TR behavior were considered. With the refinement of the model, many scholars modeled the jet flame and combustion behavior during the TR of the battery. Finally, the research object was expanded from the TR of a single battery to TRP of a battery module.

Kim et al. [80] developed an exhaust model, and to improve the accuracy of the exhaust gas combustion heat, they considered the ratio of hydrogen and volatile organic compounds in terms of the battery temperature. This model was built in a confined space and could predict the flame combustion heat release rate of the battery, but it lacked the simulation of the flame morphology and the interaction between the flame and the confined space. Wang et al. [81] further studied the TRP behavior of batteries under the influence of ceiling jet fires on the basis of their previous flame model. The model was based on the conjugate propagation modeling framework to explore the interaction between the jet flame and TRP behavior, highlighting the influence of the jet flame on the TRP behavior. The idea of the full text is shown in Figure 10.

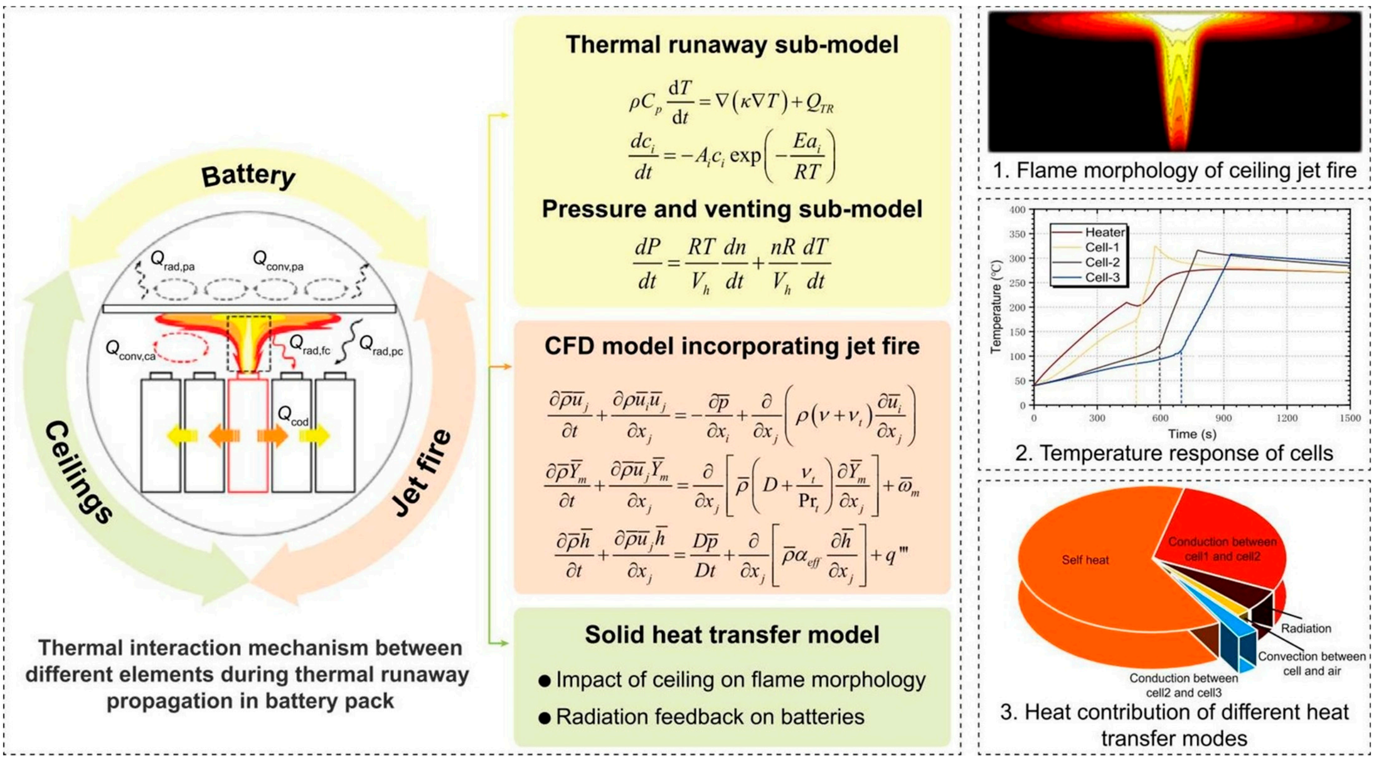

Figure 10. Modeling of flames in a confined space and its mechanism [81].

To sum up, at this stage, the simulation in a confined space is very limited, and some factors have not been fully considered, such as the lack of the radiation effect of particles in some models, and TR in a confined space triggered by mechanical abuse is not yet available, which are the directions of future research.

4. Methods of Suppressing Lithium-Ion Battery Flames

In recent years, the frequency of fire accidents in LIBs has been high, and it has become important for the safety management of batteries in electric vehicles. Whether in energy storage or in electric vehicles, the safety of batteries is no longer limited to individual batteries, but rather to the TRP between the battery module, which can exacerbate the fire hazard of batteries [12,100]. This section categorizes the existing methods of flame suppression for LIBs into active and passive methods of suppression, highlighting their superiority and limitations. Finally, a comprehensive discussion is conducted to provide certain directions for future research.

4.1. Active Suppression

For a flame to continue to burn, the "fire triangle" consists of fuel, oxygen, and heat. In the case of a battery, its safety characteristics can also be characterized by the "fire triangle". When one or more elements of the "fire triangle" are removed, battery flames can be extinguished and even prevented [101]. Based on current articles on active battery flame suppression, they can all be analyzed from a "fire triangle" perspective.

Perfluorohexanone ($C_6F_{12}O$) is a liquid that evaporates readily at room temperature and pressure [102]. It has been studied and applied by a wide range of scholars in the fire suppression of LIBs. Wang et al. [103] applied perfluorohexanone to suppress a battery fire during TR, and they effectively prolonged the TRP interval. Zhang et al. [104] investigated the suppression effects of substances such as perfluorohexanone and CO_2 on LIBs fires. They found that perfluorohexanone could quickly extinguish battery flames, while CO_2 took longer. Perfluorohexanone has a good extinguishing efficiency direct rapid cooling so that the battery cannot reach the point of ignition and played a certain role in the isolation of combustion aids. However, its operation is not very convenient, especially for the battery flame in a confined space.

Some scholars have also approached the issue from the perspective of reducing the oxygen concentration in order to inhibit the combustion of LIBs. Inert gas dilution reduces the temperature of the flame while lowering the concentration of combustion aids, and this approach is considered a promising way to suppress battery fires [24,105,106]. Previously, Lin et al. [107] and Golubkov et al. [39] investigated the suppression effect of CO_2 and N_2 on the combustion explosion of gases such as CH_4. They both found that both gases play a certain role in the suppression of combustion and explosion. The main components of the combustion gas generated during the battery TR are CH_4, H_2, and other gases. Zhou et al. [29] investigated the suppression effects of CO_2 and N_2 on battery combustion and explosion during TR. They concluded that both CO_2 and N_2 had inhibitory effects on the battery flame and explosion, and CO_2 had better effects than N_2. Weng et al. [24] investigated the effects of inert gas and oxygen concentration on the flame behavior and TRP of LIBs. They concluded that both inert gas addition and oxygen concentration reduction can suppress the battery combustion and TRP. In general, gases such as CO_2 and N_2 can be used to reduce the concentration of combustion aids by diluting oxygen and to achieve a certain cooling effect. And its operation is easier than perfluorohexanone, but the cost is relatively higher. And the fire extinguishing efficiency is not as good as that of perfluorohexanone.

In recent years, there has been an increasing number of studies utilizing fine water mist (WM) and wind methods to suppress battery fires. Miao et al. [108] investigated the suppression effect of WM on the battery flame at different stages of TR. The results showed that releasing the WM at the moment of safety valve cracking could achieve a fire extinguishing effect within a few seconds, whereas by releasing WM after the battery TR, the extinguishing time was longer and took about three minutes. Hong et al. [109] studied the suppression effect of flood cooling on fire and TRP for different types of batteries. They found that flood cooling is effective in suppressing both TRP and fire for LMO and LFP batteries, but less effective for NCM batteries. On the other hand, for the case of a confined space, Wang et al. [110] successfully suppressed the TR of the cell in a confined channel with the flame of the cell using longitudinal winds, which acted as an effective cooling agent. Jiang et al. [111] utilized WM and wind for coupling to suppress fire in a confined space, the battery enclosure. The results showed that a 4.5 m/s wind and 0.5 MPa WM had the best suppression effect, which can achieve a high heat dissipation capacity and reduce the concentration of toxic and hazardous gases. In summary, wind and WM suppress battery fires mainly by keeping the battery from reaching the ignition point. It is better for LIB fire suppression in a confined space, especially in tunnels. However, it is more demanding on the operator and has many subjective uncertainties.

By analyzing previous studies on active flame suppression, it is obvious that they all start from the fire triangle and the factors affecting the flame behavior of the battery as a way to achieve the purpose of suppressing the flame during the suppression of the battery TR. The specific battery fire triangle mechanism and the main existing active methods for suppressing the battery TR flame are shown in Figure 11. Whether it is perfluorohexanone, inert gas, or WM and wind, they each have advantages and disadvantages. They also share the common advantage of active suppression, which is the relatively high efficiency of cooling.

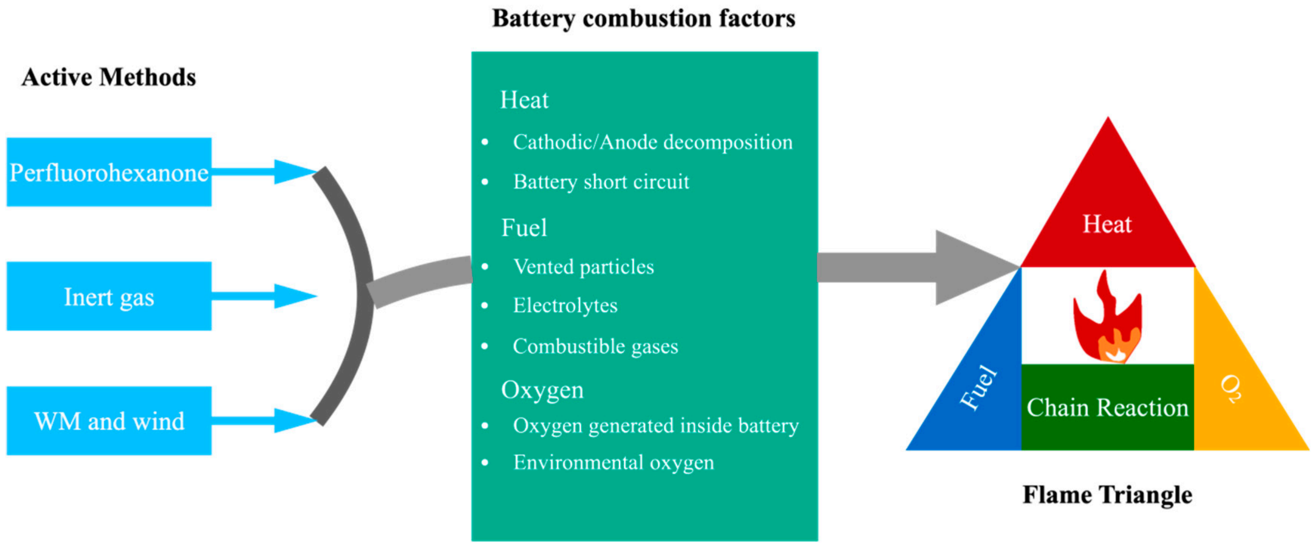

Figure 11. The specific battery fire triangle mechanism and the main existing active methods for suppressing the battery TR flame.

4.2. Passive Suppression

The opposite of the active suppression of a battery flame is the passive suppression of a battery flame. A number of studies have shown that the temperature of a battery without an effective battery thermal management system (BTMS) can rise dramatically under extreme conditions, leading to the risk of fire and explosion [112–114]. This highlights the importance of effective BTMS in the passive suppression of battery flames. Also, the intrinsic safety design of the battery is an important component of the passive suppression of a battery flame. This intrinsic safety design includes flame-retardant electrolytes [115], improved electrode materials [116], and ceramic separators [117]. Here, we can refer to the internal safety design of the battery as internal passive suppression (IPS) and the BTMS of the battery as external passive suppression (EPS).

Relevant researchers have conducted considerable research on the internal safety of batteries, especially for the design of fire protection aspects. Liu et al. [118] designed a non-flammable electrolyte by introducing low-density and low-cost fluorobenzene (FB) as a co-solvent and bridging solvent in a diluted high-Concentration electrolyte (DHCE) system through the introduction of low-density and low-cost fluoro-benzene. Shao et al. [119] designed and fabricated thermally polymerized composite gel polymer electrolytes (CPEs) for quasi-solid-state batteries. They verified that CPEs exhibited a better flame retardancy and excellent thermal stability compared to commercial PP separators (Figure 12a). Lv et al. [120] started to study IPS by improving the electrode materials for batteries.

They designed and synthesized self-extinguishing phenothiazine-based polymers using 4-bromobenzene as a flame-retardant device and 1,4-divinylbenzene as a cross-linking agent. The results showed that this designed polymer significantly shortened the self-extinguishing time without deteriorating its intrinsic thermodynamic and electrochemical properties (Figure 12b). Huang et al. [121] combined flame-retardant electrolyte additives with commercially available PE separators to improve the flame resistance of battery ceramic separators. The results showed that the improved separator helped to contribute to the safety and flame retardancy of the battery at high temperatures (Figure 12c).

On the other hand, compared to IPS, EPS improves more with the phase change material (PCM). In order to ensure a good heat dissipation at the same time, it has a certain degree of flame retardancy, which is used to suppress the battery flame [122,123]. Weng et al. [124] added the flame-retardant Al(OH)3 to PCM to improve the flame retardancy of PCM. The results showed that the flame-retardant additive played a positive role in delaying the ignition time and reducing the HRR as well as toxic gases (Figure 12d). Chen et al. [125] developed a flame-retardant phase-change material (FRPCM) and combined it with an aerogel felt. They found that the combined use of FRPCM and the aerogel felt effectively blocked TRP and suppressed the battery flame to a certain extent. Some scholars have also utilized flame retardants directly for EPS. Mei et al. [126] utilized TRRH (phenoxycyclic phospholipids), TRRM (magnesium hydroxide), and TRRS (sodium acetate trihydrate) to suppress the battery TR. They found that TRRH (phenoxycyclic phospholipids), which has a free-trapping effect, suppresses the battery flame best. The TRRS with a high heat-absorbing capacity could better control the battery surface temperature (Figure 12e).

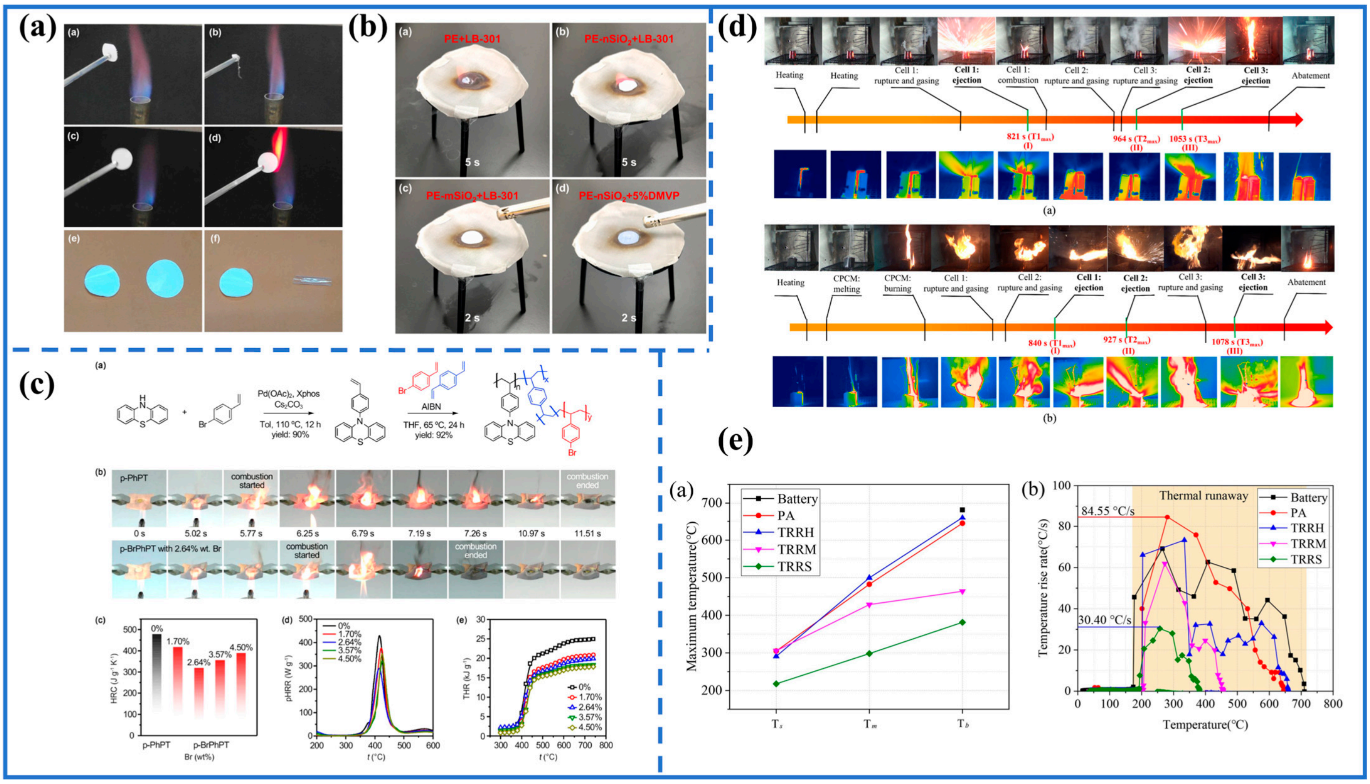

Figure 12. (**a**) Comparison of combustion experiments before and after electrolyte material modification [119]. (**b**) Comparison of combustion experiments before and after the improvement in the electrode material [120]. (**c**) Improved ceramic separator flame-retardant test [121]. (**d**) Photos and infrared images of the typical moments in the heating tests: cuboid module and tubular module [124]. (**e**) The maximum temperature of the shell, the suppression material, and the battery under different suppression conditions; The rate of temperature rise rate during TR of the battery under different suppression materials [126].

The above is a summary of passive battery flame suppression methods. For the passive suppression of battery flame, some methods start from the safety of the inside of the battery, while others start from the safety of the outside of the battery. What they have in common is that they can suppress the battery flame when the battery fire first occurs, without subjective human factors. Compared to active suppression, their disadvantage is also obvious, that is, the efficiency of cooling and flame suppression is not as high as active suppression. Therefore, in the future, the suppression of the battery flame should be strengthened in two aspects. On the one hand, the operability of active suppression should be strengthened, and on the other hand, the efficiency of passive suppression should be strengthened. Through in-depth development and research in these areas, the safety of batteries will be elevated to a new dimension.

5. Conclusions and Outlook

5.1. Conclusions

This work provides an in-depth discussion summarizing the flame behavior mechanism during the TR of LIBs and a consolidation of the current state of the methods to suppress the flame behavior of LIBs. The following conclusions are drawn:

(1) The flame intensity of LIBs during TR is influenced by external factors, such as ambient pressure and temperature, as well as internal factors like battery health and the state of charge.

(2) In a battery module, the heat contribution from the flame primarily arises from its radiant heat. The flame accelerates the TRP within the battery module, particularly in confined spaces where the heat radiation from the flame is further amplified. Currently, CFD models are the primary tools used for simulating battery flames.

(3) LIB flame suppression methods are broadly categorized into active and passive approaches. Both methods can be analyzed based on the internal and external factors affecting the battery flame and operate from the perspective of the flame triangle. Active suppression is more efficient than passive suppression but offers less intrinsic safety. A balanced approach combining both methods could enhance battery safety in the future.

5.2. Outlook

Through a comprehensive analysis of the relevant literature, the limitations were identified, and the following recommendations were made:

(1) Research on the flame behavior of batteries and the exploration of their intrinsic mechanisms is very necessary. The current research on the flame behavior in a confined space is relatively limited. On the one hand, the TRP and flame characteristics of a fully enclosed confined space in practical applications cannot be fully studied due to its spatial structure. On the other hand, for flame simulation in a confined space, multiple cell types must be considered and multiple physical fields must be coupled in order to come closer to the actual situation. Therefore, in the future, combining experiments and simulations to comprehensively verify the behavior of battery flames will be a worthwhile scheme to try.

(2) The current methods for suppressing the battery flame behavior can be divided into two main categories: active and passive suppression. At the level of active flame suppression, how to minimize human error is a challenging issue. For passive flame suppression, the development of green, energy-saving, and highly efficient safety systems will be the trend of the future, whether we start from the inside of the battery or from the environment in which the battery is located.

Further research in the field of battery flames is essential to improve the efficiency and safety of the battery module.

Author Contributions: Author Contributions: Conceptualization, M.C.; Investigation, Y.C. and Y.M.; Writing—original draft preparation, Y.M.; Writing—review and editing, Y.C. and M.C.; Supervision, Y.C. and M.C.; Funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52204213).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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