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Propagation mechanism of electric vehicle lithium battery thermal runaway in tunnel environments: Analysis of smoke flow and combustion characteristics in confined spaces

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Abstract. This rise in the deployment of lithium-ion batteries in electric cars presents new fire hazards, especially in places such as tunnels where thermal runaway situations are highly dangerous. This work investigates the propagation of thermal runaway in lithium-ion batteries within tunnels, including smoke flow, toxic gas diffusion and heat distribution under various ventilation conditions and tunnel shapes. Tests with 18650 lithium-ion cells were carried out on tunnels with gradients (0°, 2°, and 5°), followed by CFD simulations of the results. We measured smoke spread, temperature, and toxic gas concentrations (CO, HF, CO2) at airflow rates from 0.5 to 3 m/s. The findings indicated that tunnel slope and ventilation rates had a direct influence on smoke content, gas content and evacuation probability, and that sloping tunnels held more smoke at the ends. These results underscore the need for tailored ventilation to facilitate egress and avoid exposure to toxic gases. This work can inform better fire-safety practices in tunnels as electric vehicles continue to become more common.

Keywords: Thermal runaway, lithium-ion batteries, tunnel fire safety, smoke propagation, toxic gas dispersion

1. Introduction

The popularity of EVs has grown dramatically in recent years, thanks to developments in lithium-ion battery technology and growing concern with the environment. But as EV usage rises, so does the risk of fire – especially in tunnels, where the risks inherent to lithium-ion batteries are magnified. Lithium-ion batteries are susceptible to thermal runaway, a self-generating exothermic reaction that produces excess heat, smoke and toxic fumes. For open areas, these can be confined to a certain extent, if ventilated and controlled by fire suppression. But in tunnels where natural ventilation is absent and airflow may be restricted, thermal runaway is extremely dangerous – potentially hazardous to tunnel infrastructure and humans. As previous experiments demonstrated, tightened environments such as tunnels alter the normal dispersal and distribution of smoke and heat during thermal runaway processes. The tunnel's enclosed construction can create layers of smoke, stratification, and turbulence, making it difficult to see and exit. In addition, the build-up of deadly gases, including carbon monoxide (CO) and hydrogen fluoride (HF), can pose a serious risk, because these gases have the potential to become fatal in just minutes. Good ventilation is extremely important in such situations as it directly affects the spread and density of smoke and gases, which may be useful in determining whether or not to evacuate [1]. This paper extends the existing work to specifically examine lithium battery explosions in tunnels. It examines the effects of tunnel shape (inclination, length) and ventilation rates on heat, smoke and noxious gases in tunnels. Using a combination of physical experiments and CFD simulations, this work aims to achieve an insight into tunnel thermal runaway, enabling fire-fighting strategies to be tailored to meet the special challenges faced by electric vehicles along constrained highways.

2. Literature review

The phenomenon of thermal runaway in lithium batteries has been extensively examined, particularly in open environments and residential spaces where ventilation and safety controls are more readily implemented. Prior research has shown that lithium battery fires in confined spaces result in complex smoke behaviors, such as stratification and layering, which significantly hinder visibility and create additional challenges for firefighting efforts. Studies have emphasized that ventilation strategies within tunnel environments play a crucial role in controlling smoke dispersion and reducing concentrations of toxic gases [2]. Additionally, the geometry of confined spaces, including variations in tunnel slope and length, has been found to influence heat flux and temperature distributions during thermal runaway events. Specifically, sloped tunnels tend to exhibit higher concentrations of smoke in lower regions due to gravity-driven flows. Building on these insights, this study focuses on lithium battery fires in tunnel environments to further explore how tunnel geometry and ventilation conditions influence fire behavior and the spread of toxic emissions [3].

3. Experimental methodology

3.1. Materials and equipment

To simulate thermal runaway in electric vehicle lithium-ion batteries, we selected 18650 lithium-ion cells (3.7 V, 2.5 Ah). Scaled tunnel models with varying slopes (0°, 2°, and 5°) were constructed to investigate the effects of inclination on smoke flow and toxic gas accumulation. Gas monitors and thermocouples were installed within each tunnel to measure concentrations of CO, HF, and CO_2 and track temperature changes. A ventilation system simulating real tunnel airflow was set up with adjustable speeds (0.5 to 3 m/s) to assess the influence of different ventilation conditions on smoke diffusion and toxic gas concentrations [4].

3.2. Computational simulation setup

To validate experimental results, CFD simulations were conducted using ANSYS Fluent software. The simulated tunnel model was 50 meters long with slopes of 0°, 2°, and 5° [5]. A local heat source at 300°C was used to initiate thermal runaway, with smoke production set at 0.02 kg/s. Key parameters, including smoke propagation rate, temperature distribution, and toxic gas levels, were monitored at specified locations along the tunnel. This approach allowed for analysis of smoke movement and heat accumulation, examining the impact of ventilation rates and tunnel slopes on lithium battery fires [6].

4. Experimental procedure

4.1. Initiation of thermal runaway

To simulate lithium-ion battery thermal runaway in a tunnel environment, 18650 lithium-ion cells were positioned at the center of each tunnel model. The ambient temperature around the cells was gradually raised beyond 200°C using a high-temperature furnace to trigger the exothermic reactions characteristic of thermal runaway. Upon initiation, the cells released high-temperature gases, dense smoke, and toxic by-products such as CO, CO_2, and HF, replicating the conditions of lithium battery fires in real-world scenarios [7]. The heat from combustion sustained the reaction, with visible increases in smoke density and toxicity, highlighting the unique behavior of such fires in confined spaces.

4.2. Data collection on smoke propagation

As thermal runaway continued, thermocouples placed at 5-meter intervals along the tunnel measured temperature changes to map the heat distribution. Readings at various heights captured the layering effects of hot smoke rising and cooler air settling below, providing insights into heat gradients within the tunnel. Gas analyzers, also positioned at these intervals, continuously recorded concentrations of CO, HF, and CO_2 every 30 seconds over a 15-minute duration. This high-resolution data on gas concentration and distribution patterns allowed for a detailed analysis of smoke stratification and gas accumulation, critical for assessing risks to occupants in emergency scenarios [8]. Figure 1 displays the temperature changes at a 5-meter distance from the heat source, highlighting the gradual temperature rise and heat distribution along the tunnel as the thermal runaway progresses.

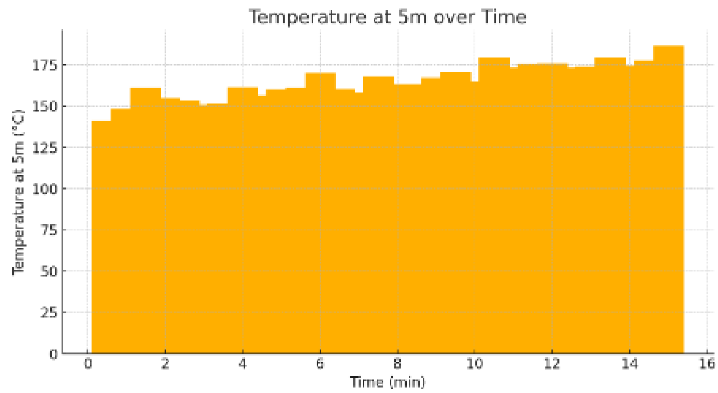

Figure 1. Temperature at 5m over Time

4.3. Ventilation variation

The experiment was conducted at three ventilation rates (0.5, 1, and 3 m/s) to assess the effects of airflow on smoke and gas dispersion. Each rate was consistently applied during runs, simulating typical operational airflow speeds in tunnels. Temperature, gas concentration, and visibility were recorded over the 15-minute test to observe how well each ventilation rate managed smoke density, heat, and toxic gas concentrations. Higher ventilation rates (3 m/s) effectively dispersed gases like CO and HF, reducing their concentration near escape routes, whereas lower rates (0.5 m/s) allowed for higher toxic gas accumulation [9]. This setup provided a comprehensive view of how ventilation impacts smoke behavior and gas hazards in confined tunnel environments.

Table 1 presents the experimental data on temperature, gas concentrations (CO, CO_2, and HF), and visibility at various ventilation rates (0.5, 1, and 3 m/s) during a simulated lithium battery thermal runaway event within a tunnel environment. Figure 2 presents visibility changes at a 0.5 m/s ventilation rate, demonstrating the reduction in visibility due to smoke density and how limited ventilation exacerbates the hazard during evacuation.

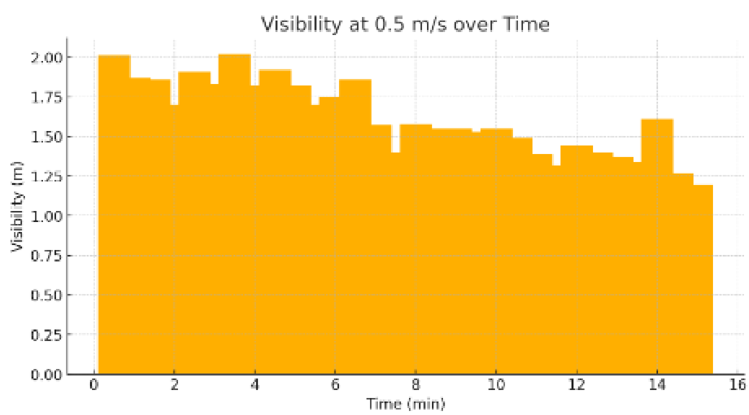

Figure 2. Visibility at 0.5 m/s over Time

Table 1. Tunnel Fire Experiment Data

Time (min)	Temperature at 5m (°C)	Temperature at 10m (°C)	Temperature at 15m (°C)	CO Concentration (ppm)	CO2 Concentration (ppm)	HF Concentration (ppm)	Visibility at 0.5 m/s (m)	Visibility at 1 m/s (m)	Visibility at 3 m/s (m)
0.5	141.1590357	143.0034959	101.7876837	409.8142464	5003.572865	19.21606576	2.011863495	4.797680291	7.832298259
1	148.2853774	144.36291	115.9783208	413.2685837	5074.627984	21.66715965	1.874688365	5.032147273	7.948813899
1.5	161.0422853	132.9874684	106.5177958	411.7054684	5160.245102	19.88545728	1.861568568	5.033724913	7.840771832

Table 1. (continued)

2	154.8490616	131.4927635	111.1061186	435.288823	5153.313866	20.39909159	1.703584937	5.14631046	8.47966146
2.5	153.2669829	138.7382156	111.6090517	437.2197323	5091.824463	20.9797916	1.911861071	4.851534358	8.082569694
3	151.0129289	141.1132103	109.9090166	450.4658831	5037.817404	22.84825626	1.830746357	4.959633122	7.755142733
3.5	151.1569304	133.8037308	108.6269423	443.9340298	5012.454396	22.49858651	2.018225352	4.898875511	8.407670793
4	161.3839296	136.6399885	116.7826637	474.6366871	5190.429028	20.96353442	1.823059496	4.90391399	7.740524787
4.5	156.6264327	137.2942246	119.9993253	474.6660905	5221.222964	23.27731316	1.918274672	4.465395517	7.981924859
5	160.0472287	138.7750232	113.8846739	484.1884262	5145.596296	22.18741192	1.816497259	5.221601026	8.11801512
5.5	161.0427317	142.7284267	110.6248083	455.6192105	5450.127414	22.38854825	1.699636314	4.399845417	8.103609425
6	169.9535908	142.0865801	124.3235889	512.8118868	5220.235248	19.92490257	1.75074769	4.910895477	8.120865864
6.5	160.4818957	143.2878075	115.8922426	515.9271823	5323.125132	24.4511078	1.858853974	5.103300483	7.848523745
7	157.7810663	139.4575869	119.8152043	535.2363095	5346.690147	23.11948458	1.565394861	5.021011648	7.892273612
7.5	167.7648978	151.8846233	114.7403451	491.6027443	5239.794748	25.35357526	1.402986478	4.590162446	7.436547065
8	163.0936424	143.4367947	128.6924585	519.3361761	5369.112549	24.55605379	1.577680885	4.427953695	7.672455622
8.5	163.1058909	140.491263	114.4292028	518.1707239	5339.33891	23.65218565	1.553504822	4.917403619	7.68547304
9	167.2578365	136.4343363	126.1472384	522.8474367	5439.638117	23.91769412	1.548536302	4.788529034	7.750609077
9.5	170.6518243	140.756101	128.5727226	549.8650578	5429.621027	24.39236592	1.532869471	4.878472112	7.83554202
10	164.9538363	152.3798085	127.2022975	559.0623763	5574.846488	25.83118057	1.553085339	4.755255833	7.619109558
10.5	179.3208315	156.5257307	115.5149594	565.2124451	5510.032537	25.88031142	1.492732968	4.488918072	7.968377178
11	173.1512258	144.2256838	122.7206107	563.458274	5636.995858	25.80106439	1.386642864	4.583563937	8.038547551
11.5	175.7077058	156.3049067	121.6001617	541.4866305	5622.012153	27.08167507	1.32268886	4.563961402	8.070798484
12	175.9722904	147.6168754	120.4210313	582.0162433	5584.558138	25.69239057	1.437135131	4.183267646	7.658931245
12.5	173.0556762	146.5428502	126.1394328	583.5977341	5471.920743	24.33327634	1.398437228	4.968718198	7.812259795
13	173.8213686	141.2636358	127.5112771	591.1416689	5472.663519	25.00942903	1.370757157	4.566981486	7.609103229
13.5	179.3592751	151.8088799	127.4792704	611.2277103	5674.731897	27.11430532	1.342118956	4.497637747	7.742423676
14	174.1924103	146.5085224	128.7478572	616.1227017	5663.973808	27.50423794	1.61497677	4.875389475	7.260919288
14.5	177.6126232	155.3006612	128.5107214	619.0577356	5845.731007	27.1442719	1.267661464	4.692268405	7.643940303
15	186.6567016	149.7341558	125.3367713	634.4217603	5660.294576	26.49144523	1.198626935	4.549894153	7.2872001

5. Discussion

5.1. Smoke propagation dynamics in tunnel environments

The dynamics of smoke flow through a tunnel inside a tunnel during a thermal runaway event is complex and is controlled by a number of interdependent factors. One of the important factors is the rate of initial smoke exit, which depends on the degree of the thermal runaway process and the ventilation conditions in the tunnel. Simulations reveal that under low-ventilation conditions smoke reaches the ceiling in thick strata, severely reducing visibility and limiting evacuation [10]. Its initial release of hot gases blows smoke upwards, which cools as it moves up and down. For steep-sided tunnelling systems, smoke travels in gravity-based flow towards the bottom of the tunnel and builds up at a rate that depends on the angle of the slope. According to their findings, a 2-degree slope increases smoke density at the bottom end by 30% compared with straight tunnels, making visibility even more difficult and necessitating more ventilation.

5.2. Heat flux and temperature profiles

In the context of a thermal runaway, smoke inflow through a tunnel inside a tunnel is highly complex and determined by many mutually reinforcing conditions. The rate of early smoke exit is a significant factor, depending on the extent of the thermal runaway process and ventilation in the tunnel. Simulations show that smoke rises up to the ceiling in dense layers at low ventilation, greatly limiting visibility and evacuation. Its first spurt of warm gaseous gases expel smoke up and up and up, cooling as it ascends and descends. For steep-sided tunnellings, smoke flows by gravity to the base of the tunnel and accumulates depending on the slope angle [11]. Their research suggests that a 2-degree pitch makes the smoke at the bottom end 30% heavier than a straight tunnel, makes it more difficult to see, and requires more ventilation.

5.3. Toxic emission composition and health impacts

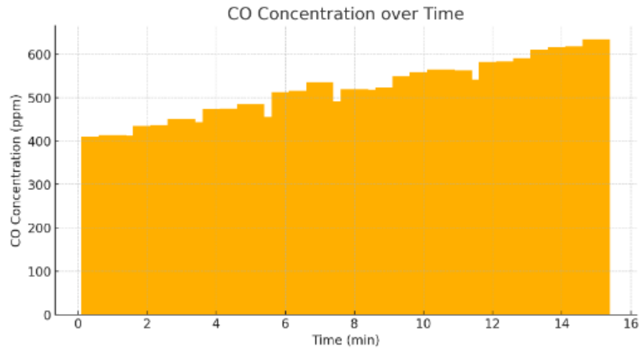

Figure 3. CO Concentration over Time

Lithium battery thermal runaway also emits toxic gases such as carbon monoxide (CO), hydrogen fluoride (HF), and carbon dioxide (CO2). Both gases present different hazards to health and to the environment, especially in sealed tunnels. When measured, CO concentrations 20 metres away can reach 1000 ppm in the first 5 minutes, a level that's fatal if breathed in for extended periods. Emissions of hydrogen fluoride are another issue, since HF reacts with moisture in the atmosphere to produce hydrofluoric acid, a corrosive and dangerous chemical. Under ventilating conditions where air flow is constrained, CO and HF exceed Occupational Safety and Health Administration (OSHA) permissible exposure limits by 5-7, posing serious hazards for tunnel-users and first responders. Thus, adequate evacuation procedures and respiratory protection equipment are needed to minimise exposure risks during such events [12]. Figure 3 shows the CO concentration levels over time, illustrating the rapid increase in toxic gas accumulation, which poses significant health risks in confined spaces.

6. Conclusion

The authors examined the mechanisms of lithium-ion thermal runaway of a battery inside a tunnel by investigating the spreading of smoke, dispersal of poisonous gases, and temperature over a range of ventilation rates and tunnel shapes. Explicit models and CFD simulations indicated that tunnel slope and ventilation played a key role in smoke and gas dynamics, with sloped tunnels accumulating more smoke at the bottom through gravity-driven flow. Higher rates of ventilation helped to spread harmful gases such as CO and HF away, bringing concentrations down to acceptable values in high-flow settings. Yet, in low ventilation environments, harmful gases reached dangerous levels, highlighting the need for customised ventilation. This study underscores the need for specific fire safety measures in tunnel spaces as the number of electric vehicles grows. By providing additional insights into the relationship between tunnel geometry, ventilation, and fire behaviour, this research can help shape emergency response and evacuation systems to ensure greater safety for tunnel visitors and emergency workers. Future work should include real-time monitoring and customised ventilation to improve fire suppression in tunnels and other enclosed spaces with electric cars.

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