Design of an IoT-Based Smoke Detector For Early Warning of Lithium-Ion 18650 Battery Explosion in Electric Vehicles

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ABSTRACT

Zahiya Z. 2026. Design of an IoT-based smoke detector for early warning of lithium-ion 18650 battery explosion in electric vehicles.

Lithium-ion batteries are widely used as the primary energy source in electric vehicles due to their high energy density and long service life; however, they present a risk of thermal runaway that can result in smoke, fire, or explosion when the battery management system fails to interrupt an overcharging process. This study aims to design and evaluate an Internet of Things (IoT)-based smoke detector prototype for providing early warning of lithium-ion 18650 battery failure caused by overcharging. An experimental method was employed using a prototype equipped with an MQ-7 gas sensor to detect carbon monoxide (CO) concentration, an Arduino Uno microcontroller for data processing, and a NodeMCU ESP8266 module for transmitting real-time notifications through the Blynk application, supported by an LCD display, LED indicators, and a buzzer alarm. The experiment was conducted by charging 18650 lithium-ion battery cells with a constant current of 3 A until an explosion occurred, using battery samples with initial states of charge (SOC) of 0% and 50%. The results indicate that the MQ-7 sensor successfully detected CO gas released during battery explosions, with concentrations ranging from 27.14 ppm to 131.55 ppm, while calibration against a CO meter showed an average error of 2.25%. Batteries with a 0% SOC produced higher CO concentrations than those with a 50% SOC due to a longer overcharging duration before explosion. The study concludes that the developed prototype can function effectively as an early warning system to reduce fire risks associated with lithium-ion battery thermal runaway in electric vehicles.

Key Words: lithium-ion battery, thermal runaway, smoke detector, Internet of Things, carbon monoxide

INTRODUCTION

A battery is an electrochemical device that converts chemical energy into electrical energy through oxidation and reduction reactions [1]. Among the many rechargeable battery chemistries that have been developed, the lithium-ion battery has become the dominant choice for portable electronic devices such as mobile phones and music players, and it is now also the main energy source for electric vehicles because of its high energy density, light weight, and long cycle life compared to other rechargeable battery types.

In Indonesia, the shift toward electric mobility is supported by Peraturan Presiden Nomor 55 Tahun 2019, which sets out a program to accelerate the use of battery electric vehicles for road transportation as part of the effort to lower fuel emissions and reduce air pollution [2]. Compared to a conventional internal combustion engine vehicle, an electric vehicle produces less noise and no tailpipe emission because its motor is powered directly by the energy stored in the battery pack, so it becomes more attractive to use as more renewable power plants are built to supply the charging network.

Several battery chemistries have been used to power electric vehicles, including lead acid, nickel cadmium, nickel metal hydride, and lithium-ion [3]. Among these options, the 18650 cylindrical lithium-ion cell is widely adopted by manufacturers such as Tesla, BMW, Nissan, and Hyundai because it offers a high energy capacity relative to its weight, a long service life, and the ability to be charged quickly [4], [5].

Despite these advantages, a lithium-ion battery pack is normally equipped with a battery management system (BMS) to keep the voltage, current, and temperature of each cell within a safe range, and when this protection system fails to respond in time, the battery can be driven into an abnormal condition known as overcharging [6]. Overcharging causes excessive lithium plating on the anode and accelerates decomposition of the electrolyte, which generates heat and gas inside the cell. If this heat is not dissipated quickly enough, it can trigger a chain of exothermic reactions known as thermal runaway, which typically begins with a gradual rise in the surface temperature of the cell, followed by smoke emission several minutes before the temperature spikes further and ignition occurs [7], [8].

The National Fire Protection Association has stated that existing data collection systems in the United States do not yet fully capture how often electric vehicle fires occur, and that there is currently no evidence showing that electric vehicles are more prone to catching fire than conventional vehicles [9]. Even so, cases of battery related fires and explosions continue to be reported, and one example that received wide media coverage happened in Montreal, Canada, when a Hyundai Kona Electric caught fire and exploded inside a home garage while parked [10]. Incidents such as this show that even though electric vehicle fires remain statistically uncommon, a single battery failure event can still cause severe property damage and personal risk, which is why an early detection method for the gas released during thermal runaway is needed before an incident escalates into open flame.

When a lithium-ion cell undergoes thermal runaway, it releases gas and smoke before any visible flame appears, and this gas will only ignite if there is enough oxygen and a sufficiently hot ignition source in the surrounding space. Because the gas release phase occurs earlier than the flame phase, gas sensing has become one of the most promising strategies for the early detection of battery failure. Several recent reviews have shown that hydrogen, carbon monoxide, carbon dioxide, and various hydrocarbon gases can all serve as early indicators of an impending thermal runaway event [11]. Among these gases, carbon monoxide is considered particularly useful for a low cost detection system because it is produced consistently from the combustion of graphite and organic separator material inside the cell, and it is also directly hazardous to human health even at a relatively low concentration, since prolonged occupational exposure above 25 to 50 ppm can already cause headache and reduced judgment in humans [12], [13].

Various IoT based fire and gas detection prototypes using low cost Arduino microcontrollers and MQ series sensors have been developed in recent years, but most of them are built to detect general smoke or LPG leakage using an MQ-2 sensor and are tested with an artificial smoke source rather than an actual battery failure event. This study takes a different approach because it applies an MQ-7 sensor, which is specifically sensitive to carbon monoxide, and tests the prototype directly on 18650 lithium-ion battery cells that are overcharged until they explode, so that the resulting detection performance reflects a condition that is closer to a real electric vehicle battery fire scenario.

Based on this background, this study was conducted to design an IoT based smoke detector prototype that uses an MQ-7 sensor to detect the carbon monoxide gas released from an overcharged 18650 lithium-ion battery, and to evaluate the detection performance of the prototype on battery samples with different initial states of charge, so that the device can later be developed further as part of an early warning and suppression system for electric vehicles.

MATERIALS AND METHODS

This research was carried out at the Fire Safety Engineering Laboratory, Building L, Faculty of Engineering, State University of Jakarta. The experimental design method was used in this study, consisting of four main stages, namely system analysis, prototype design, hardware development, and testing, so that the type of input and output modules needed for an IoT based fire detection system with Android notification could be determined properly.

Research Tools and Materials

The tools and materials used in this study are summarized in Table 1.

Table 1. Research Tools and Materials

Category	Item
Research tools	Laptop, Arduino Uno ATmega328, MQ-7 gas sensor, USB Type B cable, USB to micro USB cable, breadboard, red and green LED, resistor, buzzer (DC 3–20V), male-to-female jumper cable (9 pieces), male-to-male jumper cable, adjustable power supply (10 A), 16x2 LCD with I2C module, NodeMCU ESP8266, safety box
Research materials	18650 lithium-ion battery cells, Microsoft Word 2013, Microsoft Excel 2013, PLX-DAQ v2.11, Fritzing software, Blynk application

The battery overcharge test was conducted on 18650 lithium-ion battery cells in fresh cell condition, divided into two initial State of Charge (SOC) categories, namely 0% and 50%, with two replicate samples tested for each category. Each sample was placed inside a safety box to protect the researcher, and it was charged using a power supply with a constant current of 3 Ampere, which corresponds to the fast charging current range of 1 to 3 Ampere stated on the battery datasheet, until the cell reached an overcharged condition and exploded.

The MQ-7 gas sensor was mounted on the ceiling of the safety box directly above the tested battery sample to capture the smoke and gas released during the explosion. In addition to the MQ-7 sensor, a type K thermocouple temperature sensor was attached to the surface of the battery using aluminum foil tape, and a strain gauge sensor was attached in the same way to monitor the physical deformation of the battery casing during the test. Voltage, current, and resistance were measured using an AVO meter connected between the power supply and the battery terminal, while data acquisition from the sensors was carried out using PLX-DAQ software and recorded on a laptop, as illustrated in the prototype testing schematic in Figure 1.

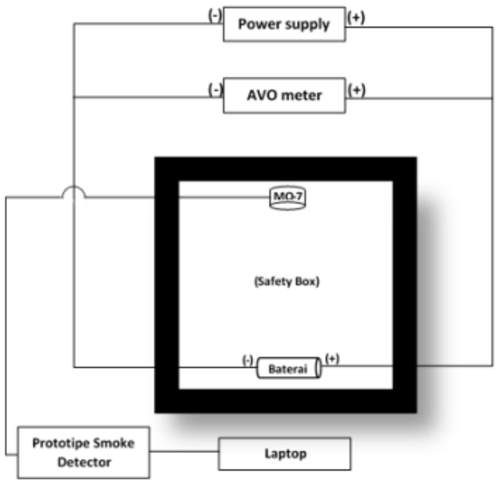

Figure 1. Smoke Detector Prototype Testing Schematic

Prototype Design and Working Principle

The overall research procedure followed the flow chart in Figure 2, starting with a literature review, prototype design, and preparation of tools and materials, followed by the parallel assembly of the smoke detector prototype and the battery testing apparatus. Before the prototype was installed on the testing apparatus, a calibration comparison between the MQ-7 sensor and a reference CO meter was carried out repeatedly until the reading error was below 5%, after which the prototype was tested on the battery samples, and the resulting data were collected, processed, and discussed to reach a conclusion.

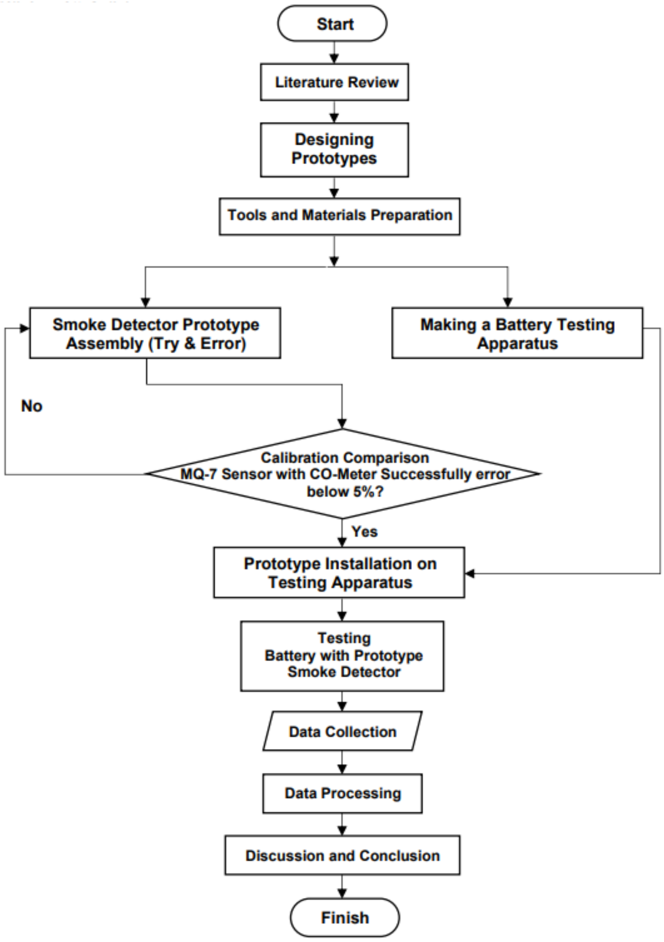

Figure 2. Research Flow Chart

The purpose of the prototype is to detect the smoke and gas emitted when an 18650 lithium-ion battery is overcharged until it reaches a hazardous condition. The MQ-7 sensor detects the exhaust gas released from the battery through its analog output on pin A0, and the Arduino Uno ATmega328P R3 microcontroller processes this analog data before commanding the connected outputs to respond according to the programmed threshold. The NodeMCU ESP8266 module captures the WiFi signal and transmits the processed data to the Blynk application on a smartphone through serial communication with the Arduino, in which the NodeMCU acts as the receiver (RX) and the Arduino as the transmitter (TX). The LCD combined with an I2C module displays the sensor reading directly to the user, while the buzzer and LED provide an audible and visual alarm when smoke or gas is detected above the set threshold. The working principle of the prototype is illustrated in Figure 3.

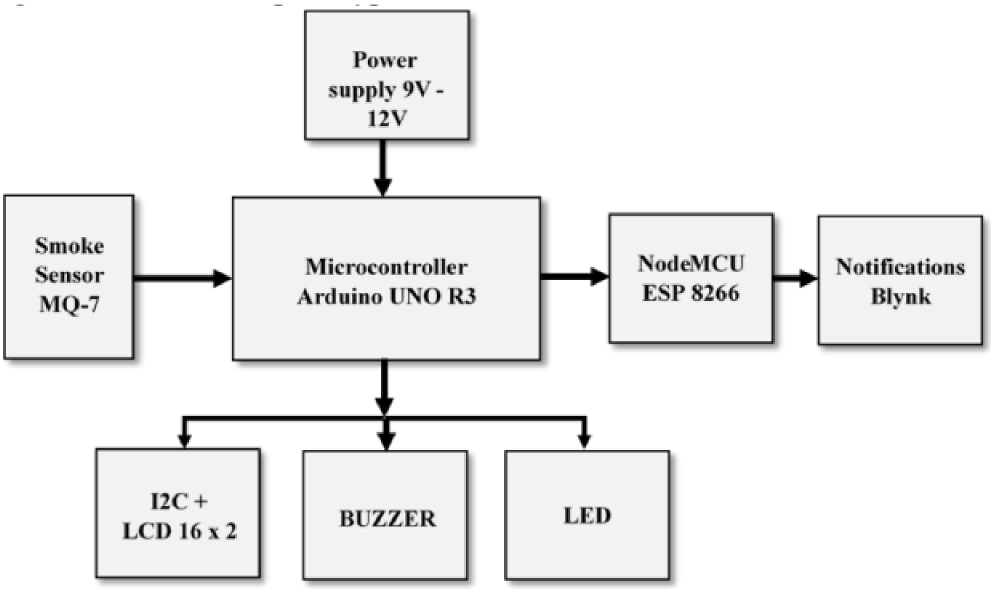

Figure 3. Working Principle of the Prototype

The detection logic of the prototype is presented in the flowchart in Figure 4. After the input and output pins are initialized, the MQ-7 sensor continuously reads the surrounding air through the Arduino analog to digital converter using the analogRead(A0) command. If the carbon monoxide concentration detected is below 25 ppm, the system is considered to be in a safe condition, and the green LED remains active while the buzzer stays off. If the concentration exceeds 25 ppm, the system switches to a danger condition, in which the red LED and buzzer are activated and the NodeMCU sends a warning notification to the user through the Blynk application.

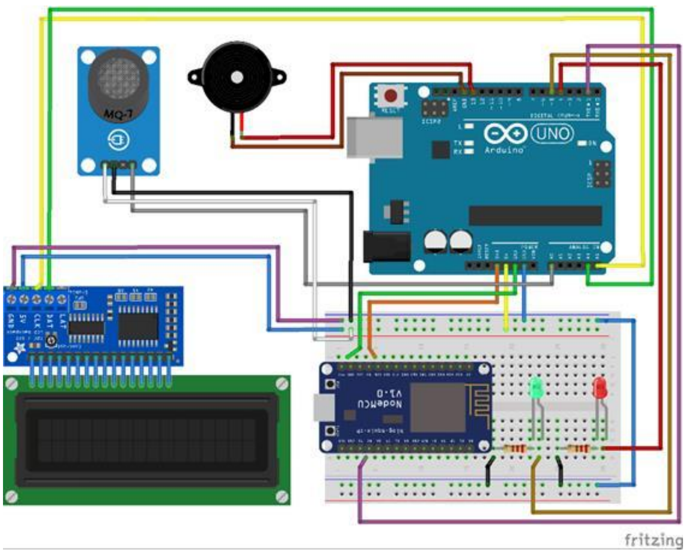

Figure 4. Flowchart of the Prototype Detection Process

Circuit Assembly and Wiring

The complete wiring diagram of the prototype was designed using Fritzing software and is shown in Figure 5. The main components consist of a 9 to 12 Volt power supply, an Arduino Uno ATmega328 microcontroller, a NodeMCU ESP8266 module, an MQ-7 sensor, a 16x2 LCD with an I2C module, red and green LED indicators, and a buzzer, which are connected together using jumper cables, a 2.2 ohm resistor, and a breadboard. The detailed connection between each component pin and the corresponding Arduino board pin is presented in Table 2.

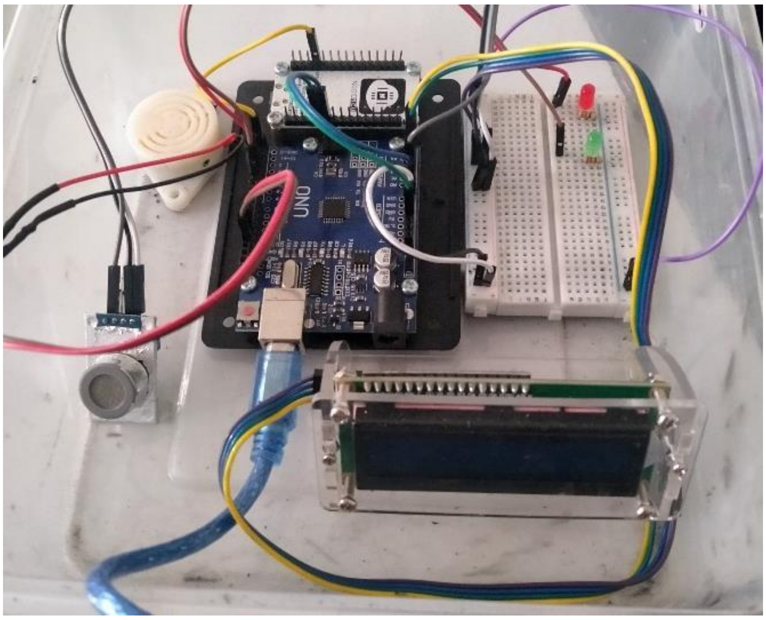

Figure 5. Smoke Detector Circuit Design

Table 2. Wiring Configuration Between Prototype Components and the Arduino Board

Component Name	Component Pin	Arduino Board Pin
NodeMCU	3.3V	3.3V
NodeMCU	GND	GND
NodeMCU	RX	TX
MQ-7	VCC	5V
MQ-7	GND	GND
MQ-7	A0	A0
LCD 16x2 + I2C	GND	GND
LCD 16x2 + I2C	VCC	5V
LCD 16x2 + I2C	SDA	A4
LCD 16x2 + I2C	SCL	A5
Green LED	(+)	D6
Green LED	(−) + Resistor 2.2 ohm	GND
Red LED	(+)	D4
Red LED	(−) + Resistor 2.2 ohm	GND
Buzzer	(+)	D13
Buzzer	GND	GND

During testing, the smoke concentration read by the MQ-7 sensor was recorded continuously in parts per million (ppm) together with the battery voltage, surface temperature, and physical deformation until the battery exploded. The calibration accuracy of the MQ-7 sensor was evaluated by comparing its reading with a reference CO meter using Equation 1, and the average error of all measurements was calculated using Equation 2.

$$\text{Error (\%)} = ((\text{Sensor MQ-7} - \text{CO Meter}) / \text{Sensor MQ-7}) \times 100\% \quad \text{.................} \ (1)$$

$$\text{Average Error} = \text{Total Error} / \text{Amount of Data} \quad \text{.................} \ (2)$$

RESULTS AND DISCUSSION

Smoke Detector Prototype Realization

The assembled prototype hardware, consisting of a 9 to 12 Volt power supply, an Arduino Uno ATmega328 microcontroller, a NodeMCU ESP8266, an MQ-7 sensor, a 16x2 LCD with I2C module, LED indicators, and a buzzer, is shown in Figure 6. All components were wired according to the design in Figure 5, with the MQ-7 sensor connected to analog pin A0 to read the analog to digital converter value, while the LCD, LED, buzzer, and NodeMCU function as the system outputs.

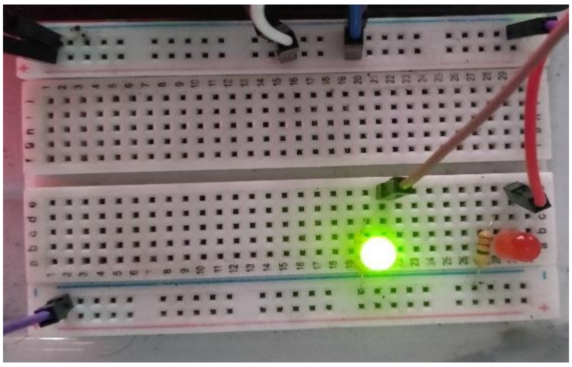

Figure 6. Physical Assembly of the IoT Smoke Detector Prototype

LCD, LED, and Notification Output

The 16x2 LCD screen displays a startup message when the prototype is powered on, followed by a real time carbon monoxide reading in ppm during operation, as summarized in Table 3. Table 3 also shows that the LCD screen indicates a safe condition when the CO reading is below 25 ppm and switches to a hazard warning labeled “BAHAYA! BATERAI BERASAP” when the reading exceeds this threshold, which corresponds to the danger condition shown in Figure 7.

Table 3. Description of the LCD Display Output

No	LCD Display Content	Description
1	“Smoke Detector Starting” / “Made By: Zalfa Zahiya”	Display shown when the prototype is first powered on
2	“Kondisi Aman, Tidak ada Asap” / “Kadar Asap CO :17.40 ppm”	Display shown when the MQ-7 sensor detects a carbon monoxide level below 25 ppm
3	“BAHAYA! BATERAI BERASAP” / “Kadar Asap CO :299.55 ppm”	Display shown when the MQ-7 sensor detects a carbon monoxide level above 25 ppm

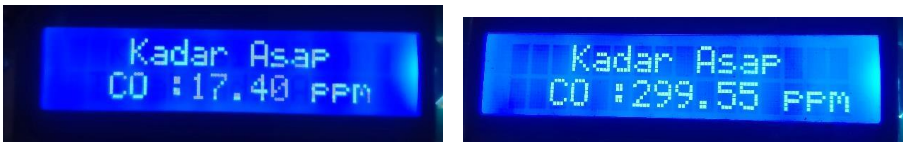

Figure 7. LCD display under a safe condition (a) and a hazard condition (b)

In the same way, the LED indicator changes from green to red once the threshold is crossed, as illustrated in Figure 8, while the buzzer produces an audible alarm at the same moment.

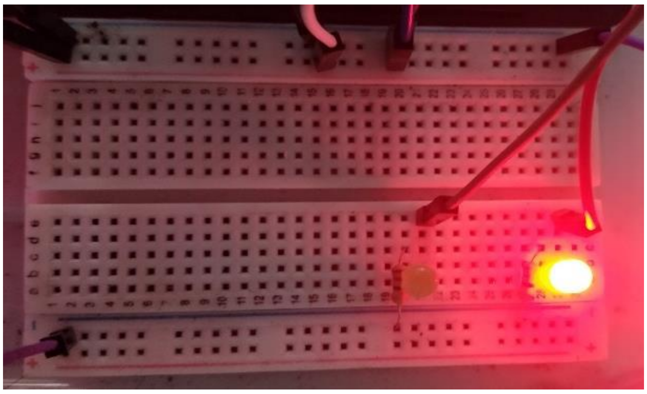

Figure 8. LED indicator under a safe condition (a) and a hazard condition (b)

When the prototype detects a hazardous concentration of carbon monoxide, the NodeMCU ESP8266 also forwards this information to the Blynk application on the user's smartphone through a WiFi connection, producing a pop up notification and a system warning message as shown in Figure 9, so that the user can receive an alert even without directly looking at the LCD or hearing the buzzer.

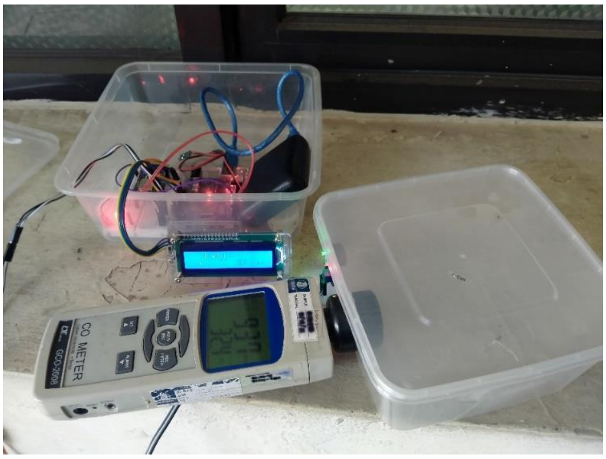

Figure 9. Pop Up Notification Displayed on the Blynk Application

MQ-7 Sensor Calibration

Before being used on the battery samples, the MQ-7 sensor was calibrated against a reference CO meter by introducing smoke into a closed container fitted with both sensors, as shown in Figure 10. The comparison was carried out for approximately 7 minutes, and the reading became stable after about 2 minutes, which corresponds to the sensor warm up time of around 90 seconds stated in the MQ-7 datasheet. The resulting comparison between the two instruments is presented in Figure 11.

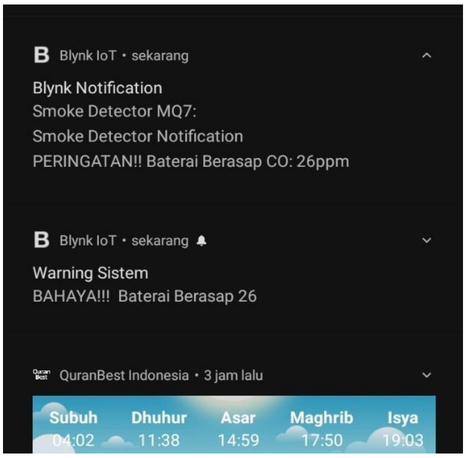

Figure 10. MQ-7 Comparison Calibration Setup with a Reference CO Meter

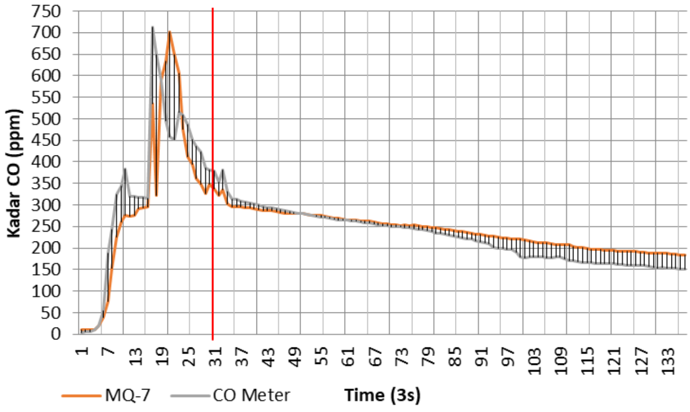

Figure 11. MQ-7 Comparison Calibration Chart Against the Reference CO Meter

Using Equation 1 and Equation 2, the average reading error between the MQ-7 sensor and the CO meter was found to be 2.25%, which indicates that the sensor readings are close enough to the reference instrument to be used for the subsequent battery overcharge test. Because the MQ-7 sensor has an effective detection range of about 20 to 20000 ppm, readings below 20 ppm in clean air were treated as background noise and considered to represent a condition with no significant carbon monoxide present (Senthil Babu and Nagaraja 2018).

Battery Overcharge Test at 0% State of Charge

In the first test with a battery at 0% state of charge, the MQ-7 sensor recorded an initial CO concentration of 115.07 ppm, and the battery exploded after 8 minutes 53 seconds of overcharging at a surface temperature of 97.25 °C, a voltage of 9.15 V, and a state of charge that had risen to 512.5% of its original value, as shown in Figure 12. In the second test under the same 0% state of charge condition, the sensor detected an initial CO concentration of 131.55 ppm, and the explosion occurred after 8 minutes 39 seconds at a temperature of 115.75 °C and a state of charge of 420.83%, as shown in Figure 13.

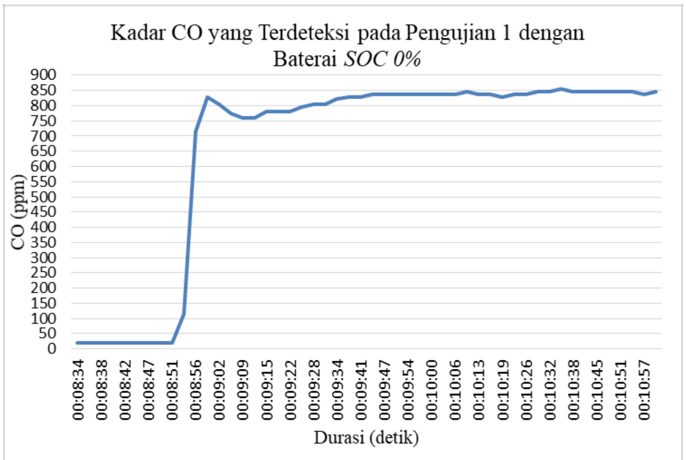

Figure 12. Graph of CO Levels in Test 1 at 0% Battery State of Charge

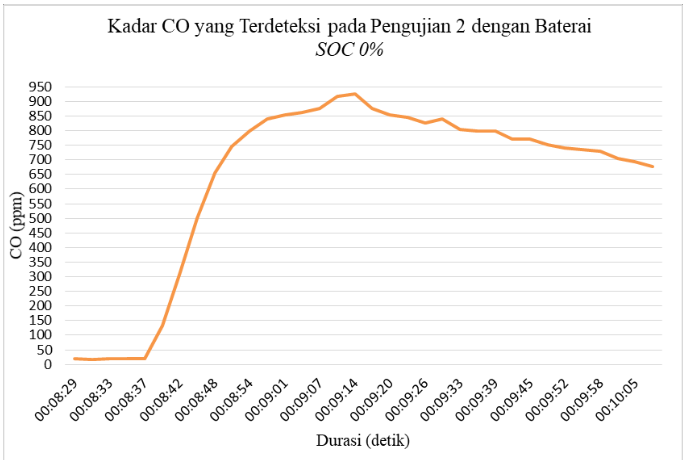

Figure 13. Graph of CO Levels in Test 2 at 0% Battery State of Charge

The comparison between the two tests in Figure 14 shows that the CO concentration pattern differed slightly between the two samples even though both used fresh battery cells, which suggests that the internal condition of a lithium-ion cell can vary between individual units and affect how quickly thermal runaway develops. Both cells began to physically deform at an average surface temperature of around 75 °C, and the physical condition of the battery casing after the explosion, which shows melting of the outer plastic layer, is presented in Figure 15. This deformation reflects the internal pressure buildup that occurs during thermal runaway, which eventually forces the release of smoke and diaphragm material through the positive terminal of the cell, consistent with the mechanism described by Han et al. (2025) and Kong et al. (2023).

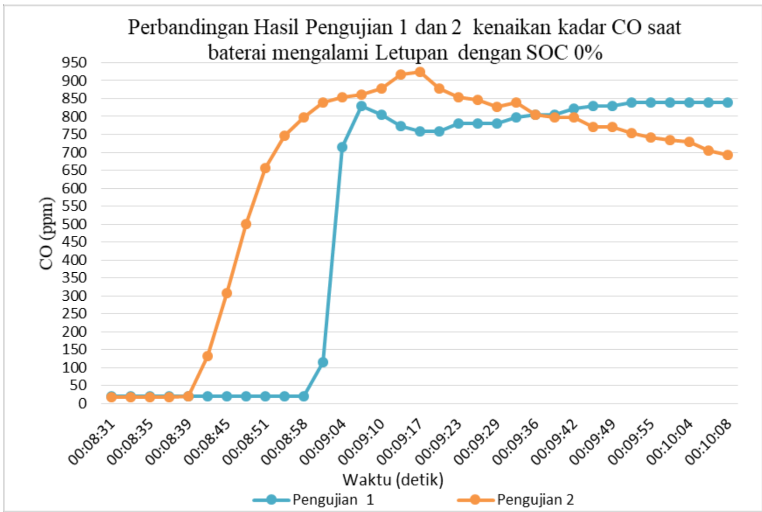

Figure 14. Comparison Chart of CO Levels in Test 1 and Test 2 at 0% Battery State of Charge

Figure 15. Physical condition of the battery after explosion at 0% state of charge, Test 1 (a) and Test 2 (b)

Battery Overcharge Test at 50% State of Charge

For the battery samples with an initial 50% state of charge, the first test recorded an initial CO concentration of 27.14 ppm, with the explosion occurring after 5 minutes 16 seconds at a temperature of 107.5 °C, a voltage of 5.27 V, and a state of charge of 189.16%, as shown in Figure 16. The second test recorded an initial CO concentration of 29.55 ppm, with the explosion occurring after 6 minutes 17 seconds at a temperature of 80.5 °C and a state of charge of 250%, as shown in Figure 17.

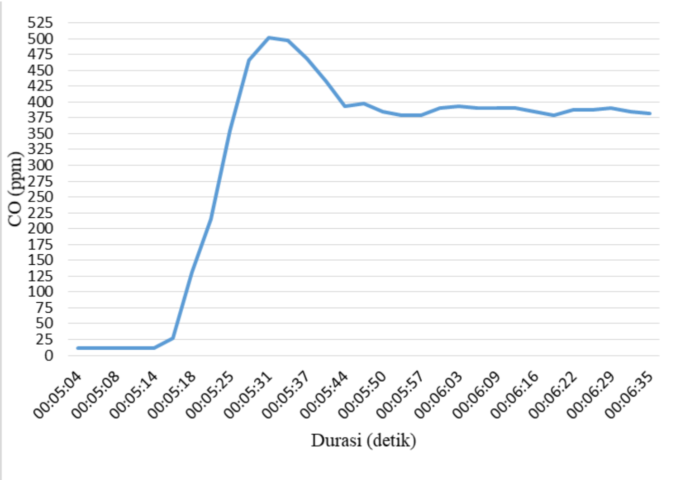

Figure 16. Graph of CO Levels in Test 1 at 50% Battery State of Charge

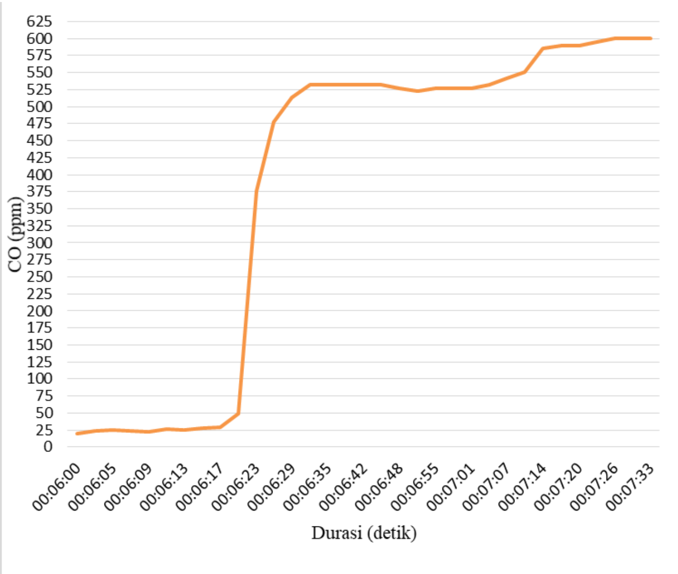

Figure 17. Graph of CO Levels in Test 2 at 50% Battery State of Charge

As shown in the comparison chart in Figure 18, the CO concentration at the moment of explosion for the 50% state of charge samples was lower than that of the 0% state of charge samples, which is consistent with the shorter overcharging duration needed to reach the explosion point when the battery starts from a higher initial charge. The physical deformation of the battery casing under this condition was comparatively mild, showing only slight melting of the outer plastic layer before it ruptured and released smoke, as presented in Figure 19.

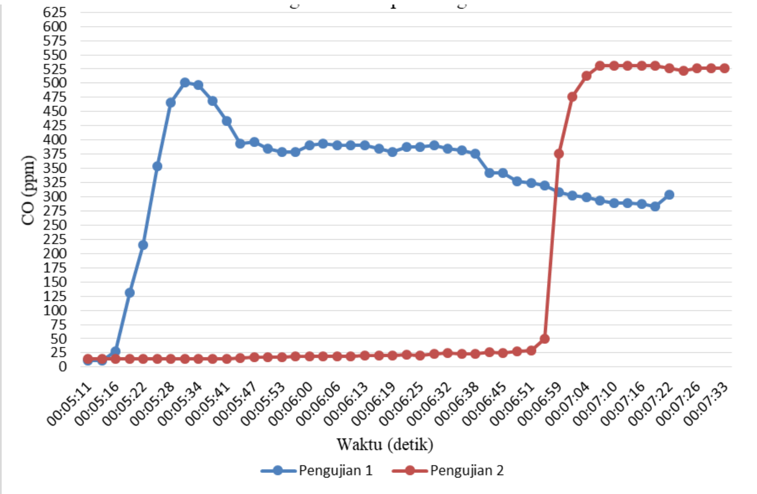

Figure 18. Comparison Chart of CO Levels in Test 1 and Test 2 at 50% Battery State of Charge

Figure 19. Physical condition of the battery after explosion at 50% state of charge, Test 1 (a) and Test 2 (b)

Discussion

Overall, the test results indicate that the amount of carbon monoxide gas released at the moment of explosion tends to be higher for batteries with a lower initial state of charge, since these batteries require a longer overcharging period before failure occurs, allowing more decomposition reactions and gas generation to take place inside the cell before venting [11]. This finding is in line with previous studies showing that overcharge duration and current strongly influence the severity of thermal runaway in 18650 cells, and that once the internal protection layer of the separator melts, the battery loses its ability to interrupt the internal short circuit that continues to drive the thermal runaway process [8].

From a fire safety perspective, the ability of the MQ-7 sensor to detect a rising CO concentration several minutes before the battery physically explodes shows that gas based early detection can give additional response time for a driver or a suppression system to act before an electric vehicle fire develops into an uncontrollable event. This finding supports the argument that battery management system failure should always be backed up with an independent physical detection layer rather than relying on the BMS alone [6]. The average sensor error of 2.25% obtained in this study also indicates that a low cost MQ-7 sensor can provide a sufficiently reliable reading for this kind of early warning application, although periodic calibration is still required to maintain its accuracy over time, as also noted in previous calibration studies on the same sensor type [14].

CONCLUSION

This study has successfully designed and tested a prototype Internet of Things based smoke detector that uses an MQ-7 sensor to give an early warning of thermal runaway in an 18650 lithium-ion battery used in electric vehicles. The prototype is able to display the carbon monoxide reading on an LCD screen, activate an LED and buzzer alarm, and send a real time notification to a smartphone through the Blynk application whenever the carbon monoxide concentration exceeds the 25 ppm threshold. The calibration test showed that the MQ-7 sensor produced an average reading error of only 2.25% when compared to a reference CO meter, which confirms that the sensor is reliable enough to be used for this application. The battery overcharge test further showed that a battery with a 0% state of charge released a higher carbon monoxide concentration before exploding, at 115.07 ppm and 131.55 ppm in the two test repetitions, compared to a battery with a 50% state of charge, which released 27.14 ppm and 29.55 ppm, since the lower state of charge required a longer overcharging duration and therefore allowed more gas to build up inside the cell before the explosion occurred. Based on these findings, it can be concluded that an MQ-7 based smoke detector prototype is capable of detecting the carbon monoxide gas produced during the thermal runaway of an 18650 lithium-ion battery and has the potential to be developed further as part of an early warning or automatic suppression system for electric vehicles.

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