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Design and Fabrication of an Automated Liquefied Petroleum Gas (LPG) Fire Suppression System

Mercy Kitimbo[1], Obbo Timothy[2], Hallan Oloa[3], Bashir Mutesasira[1]

[1]Uganda Industrial Research Institute, Kampala, Uganda
[2]Faculty of Engineering, Department of Mining Chemical and Petroleum Engineering, Kyambogo University, Kampala, Uganda
[3]College of Computing and Information Sciences, Makerere University, Kampala, Uganda
Email: mkitimbo@kyu.ac.ug

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Abstract

This project addresses the critical issue of fire safety, particularly in environments where liquefied petroleum gas (LPG) is used. LPG presents a significant fire hazard due to its combustible nature, posing risks to both life and property. The Automated LPG Fire Suppression System (ALPG-FSS) aims to mitigate these risks by providing an autonomous and efficient method of detecting and suppressing LPG fires. The system employs infrared flame detection sensors to identify fire occurrences and a microcontroller to analyze sensor data and trigger appropriate responses. Upon detecting a fire, the system activates a blower fan to disperse a suppression agent, such as sodium bicarbonate, aimed at extinguishing the flames. Additionally, an alarm system alerts occupants to the presence of a fire, facilitating timely evacuation and further enhancing safety measures. This system further allows for remote monitoring and control on a mobile device via a Blynk mobile application that accesses system data and status from the ESP 32 microcontroller. The technology behind the ALPG-FSS combines hardware components, such as sensors, microcontrollers, and actuators, with software algorithms to create an integrated fire suppression solution. Infrared flame detection sensors enable the system to detect LPG fires based on the presence of infrared radiation emitted by flames. The microcontroller serves as the brain of the system, processing sensor data and executing predefined algorithms to initiate suppression actions when necessary. Actuators, such as the blower fan, provide the mechanical means to disperse suppression agents effectively. Overall, the ALPG-FSS represents a sophisticated integration of hardware and software technologies, tailored to address the specific challenges associated with LPG fire hazards and enhance fire safety in various settings.

Keywords

Internet of Things (IoT), Liquefied Petroleum Gas (LPG), Fire Suppression System, Remote Monitoring and Control, Blynk Mobile Application, Fire Hazards, Fire Safety, Gas Leakage Detection

1. Introduction

1.1. Background

For all the benefits that LPG can bring, many households are reluctant to make the switch because of concerns about the safety of handling and using the fuel. Liquefied Petroleum Gas (LPG), a clean fuel obtained as a by-product of petroleum refining processes, is globally used as a multipurpose material in the industrial chemical, commercial, residential, transportation and other sectors of economy [1]. LPG is colorless, odorless and heavier than air, therefore, if a cylinder is defective and leaking, it could cause a volatile explosive atmosphere and life safety hazards without us being aware. Addressing issues related to safety can be both an asset and liability to the growth of LPG as a widespread and viable clean cooking fuel.

Manual fire response and intervention is always required to mitigate fire events, provide for the safety of lives and is assumed to be present. While these measures have proven effective to some extent, they are subject to limitations inherent to human response time and error. A report on lessons learned from LPG accidents attributed potential disaster contributors to; very late emergency isolation, failure of the overall system of protection, and no gas detection system [2].

In this context, the development of an advanced, automated LPG fire suppression system emerges as a vital endeavor. Such a system would significantly enhance fire safety by drastically reducing response times and mitigating the risks associated with human intervention. It promises to provide a proactive and reliable solution for detecting and suppressing LPG fires swiftly, thereby safeguarding lives, property, and the environment.

Before 1990, fire safety projects dealing with thermal resistance of buildings mainly focused on manual systems such as fire hose reels, fire buckets and manual foam fire extinguishers. In more recent years, there has been an increasing interest in designing practical protection systems against fire. Some of these include protection by mechanical systems such as fire sprinklers [3]. While these systems have proven effective for traditional fires, the explosion of LPG is characterized by a high diffusion rate and rapid combustion speed [4], necessitating a specialized approach. As a result, there is a significant void in the literature covering the design and construction of an automated LPG fire suppression system.

The significance of this study is highlighted by the possibility that this research will revolutionize fire safety procedures in LPG-related sectors and residential areas. By addressing the gap in current knowledge and technology, this study seeks to contribute to the development of a cutting-edge fire suppression system capable of detecting and extinguishing LPG fires with unparalleled speed and precision. Since the fire suppression uses automatic means to get activated, it means that very little expertise will be required to operate the system. To battle fires, the system can also use inert gases or dry chemicals. This is an assurance that the system will not endanger human health [5].

This project aims to fill a knowledge gap by creating an advanced automated LPG fire suppression system that utilizes cutting-edge technology and innovative engineering solutions. This system will incorporate reliable fire detection methods, rapid response procedures, and environmentally friendly suppression agents, setting a new safety standard for LPG handling and storage. Ultimately, this research seeks to make a substantial contribution to fire safety engineering and enhance the protection of lives and property in LPG-related settings.

1.2. Problem Statement

In contemporary environments heavily reliant on Liquefied Petroleum Gas (LPG) as a primary energy source, the lack of proactive fire safety measures presents a critical gap in current safety protocols. Conventional fire suppression systems often reactively respond to fire incidents, potentially leading to catastrophic outcomes. Simultaneously, the absence of an automated and intelligently integrated LPG Fire Suppression System (ALPG-FSS) exacerbates this issue, leaving industrial, residential, and commercial spaces vulnerable to LPG-related fire hazards. To address this pressing safety concern, my research aims to design and fabricate an ALPG-FSS that leverages Arduino and Internet of Things (IoT) technologies. This system seeks to bridge the gap in LPG fire safety by proactively detecting potential fire hazards, initiating rapid fire control measures, and enabling remote monitoring, ultimately ensuring a safer environment for LPG utilization.

1.3. Objectives

1.3.1. General Objective

The main objective of this study is to design and fabricate an ALPG-FSS that proactively detects potential fire hazards and initiates rapid fire control measures.

1.3.2. Specific Objectives

i. To assess the performance and reliability of the system.
ii. To enable remote monitoring and control of the system.
iii. To compare the capabilities and efficiency of the system to existing fire safety measures.

1.4. Research Questions

1. How can an Automated LPG Fire Suppression System (ALPG-FSS) enhance LPG fire safety effectively?

2. What are the technological requirements for designing an efficient ALPG-FSS?

3. How do Arduino and IoT technologies affect real-time LPG fire detection and response in the ALPG-FSS?

1.5. Research Justification

In today's scenario, there's pressing need to enhance safety measures in LPG handling and storage, where human-operated fire safety systems exhibit inherent limitations in terms of response time and reliability. LPG fires pose a significant risk to human lives, property, and the environment, making the development of an automated LPG fire suppression system crucial.

By addressing this gap in current knowledge and technology, this research seeks to provide a proactive and efficient solution, minimizing the potential for catastrophic incidents and their consequences. This system has the potential to revolutionize fire safety practices in LPG-related industries and residential settings, significantly advancing both the field of fire safety engineering and the protection of individuals and assets from LPG-related fire hazards.

1.6. Significance

This research holds significant relevance as it addresses a critical gap in fire safety technology, particularly in the context of Liquefied Petroleum Gas (LPG) handling and storage. Current manual fire suppression methods have inherent limitations, including delayed response times, posing significant risks to human lives, property, and the environment.

By pioneering the development of an automated LPG fire suppression system, this study not only promises to revolutionize safety practices in LPG-related industries and residential settings but also offers the potential to save lives, minimize property damage, and reduce environmental hazards associated with LPG fires. Furthermore, this research aligns with the broader goals of enhancing fire safety and disaster prevention, making it socially and technologically significant in our pursuit of safer and more sustainable communities.

2. Literature Review

This section offers a concise exploration of pertinent literature, laying the foundation for understanding fire suppression technologies. It delves into theoretical principles, empirical studies, and technological advancements, providing essential insights for the development of an Automated LPG Fire Suppression System.

2.1. Theoretical Literature Review

2.1.1. Introduction to LPG Fire Safety

Liquefied Petroleum Gas (LPG) is a versatile and commonly used fuel source comprised of propane and butane gases. It finds applications in heating, cooking, transportation, and more due to its clean-burning characteristics and high energy content [6]. However, the importance of LPG safety cannot be overstated, as accidents and mishandling can lead to hazardous situations, particularly fires and explosions. The safety of LPG is of paramount concern in various industries where it is utilized, as it not only protects lives and property but also has broader implications, including environmental preservation and public well-being.

Safety in industries that employ LPG is vital, spanning sectors such as hospitality, transportation, manufacturing, and agriculture. In these industries, LPG is essential for operational efficiency, but its energy-rich nature can pose significant risks when not handled properly. Safety measures must encompass LPG storage, transportation, leak detection, and emergency response procedures. Of utmost importance is fire safety, as fires involving LPG can escalate rapidly due to its volatile properties and high energy content [7]. Preventing, detecting, and suppressing LPG fires is crucial to mitigate potential hazards and protect both workers and the community.

LPG safety goes beyond individual industries, affecting environmental preservation and public welfare. Accidental LPG leaks can release greenhouse gases, contributing to climate change, while fires resulting from mishandling can lead to injuries, fatalities, and property damage [7]. As a response to these safety concerns, industries and regulators prioritize safety protocols, training, and adherence to established standards. The design and implementation of LPG fire suppression systems play a vital role in this context, helping to prevent, detect, and control LPG fires and, in turn, ensuring the responsible use of this valuable energy resource.

2.1.2. Foundations of Fire Safety

Fire safety is a fundamental aspect of industrial and residential security. It rests upon a firm understanding of the core principles of fire behavior and control. Two essential theories that underpin fire safety are the Fire Triangle and the Fire Tetrahedron. These theories help comprehend the conditions necessary for a fire to occur and guide the development of effective fire suppression strategies.

The Fire Triangle, a foundational theory in fire safety, delineates the three essential elements for igniting and sustaining a fire: fuel, oxygen, and an ignition source, as illustrated in **Figure 1**. In the case of LPG fires, this theory's direct applicability is evident, where LPG serves as the combustible fuel, atmospheric oxygen acts as the oxidizer, and ignition sources, such as sparks or open flames, initiate the chemical reaction. The removal or control of any of these elements becomes vital for effective fire suppression.

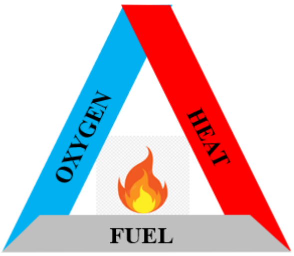

Figure 1. An illustration of the fire triangle.

Building upon this, the Fire Tetrahedron extends the theory by introducing a fourth element, chemical reactions, emphasizing their role in fire sustainability. In the context of LPG fires, where fuel and oxygen are ever-present, managing heat and disrupting the ongoing chemical reactions are essential strategies. Effective fire suppression focuses on cooling the fire and inhibiting these chemical processes, thereby breaking the Tetrahedron and extinguishing the fire. Understanding these theories is central to addressing LPG fire safety and mitigating potential hazards [8]. **Figure 2** illustrates an inclusion of chemical reactions to the three essential elements for igniting and sustaining a fire that make a basis of formation of the fire tetrahedron.

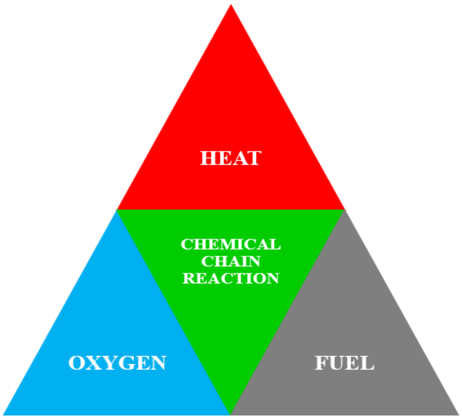

Figure 2. An illustration of the fire tetrahedron.

2.1.3. LPG Fire Behavior

Liquefied Petroleum Gas (LPG) fires possess distinct characteristics that set them apart from other types of fires. These characteristics stem from the unique properties of LPG, which is predominantly composed of propane and butane gases. One of the primary characteristics is the remarkable flammability of LPG. LPG is highly combustible, meaning it readily ignites when exposed to an ignition source. This flammability is driven by the fuel's narrow flammable range, which indicates the concentration of LPG vapor in the air that can sustain combustion [9]. LPG's flammability makes it a versatile and efficient energy source but also underscores the need for rigorous safety measures in its handling and use [7].

Volatility is another distinctive feature of LPG fires. LPG is stored and transported in a liquid state under pressure but readily vaporizes when released into the atmosphere. This rapid vaporization results in the formation of a gaseous fuel cloud, which can expand and disperse quickly. The volatility of LPG means that, in the event of a leak or release, the flammable gas can spread rapidly, posing potential fire hazards over a considerable area [9]. Therefore, effective safety measures and fire suppression strategies must be in place to manage these volatile characteristics.

Additionally, understanding LPG fires requires consideration of vapor density. LPG vapor is denser than air, which means it tends to sink and accumulate in lowlying areas. This property can lead to the formation of flammable pockets in confined spaces, basements, or depressions, making LPG fires particularly hazardous in such environments [9]. Awareness of this vapor density characteristic is critical for safety planning, especially in industrial settings where LPG is commonly used.

Chemical Reactions and Behaviors Specific to LPG Fires

LPG fires exhibit unique chemical behaviors that set them apart from fires involving other fuels. When ignited, LPG undergoes a series of chemical reactions. The initial reaction involves the vaporization of LPG, transitioning it from a liquid to a gaseous state. This phase change is accompanied by a significant release of energy in the form of heat. It is this heat release that sustains the fire, creating a feedback loop of increasing temperature and fuel vaporization [10].

Equations of Vaporization:

- Propane (C3H8): $C_3H_{8(l)} \rightarrow C_3H_{8(g)}(15.7\ \text{KJmol}^{-1})$
- Butane (C4H10): $C_4H_{10(l)} \rightarrow C_4H_{10(g)}(21.0\ \text{KJmol}^{-1})$

One of the distinctive features of LPG combustion is the clean, nearly invisible flame produced during combustion. The absence of visible smoke or soot in LPG fires is due to the complete combustion of hydrocarbons in the fuel [11]. While this may seem advantageous in terms of reduced environmental impact, it presents a challenge in terms of early fire detection, as the absence of visible smoke can delay awareness of the fire's presence.

2.1.4. Sodium Bicarbonate as a Suppression Agent for LPG Fires

LPG fires, driven by the combustible nature of propane and butane gases, necessitate the use of agents that can effectively control and extinguish them. One such agent is sodium bicarbonate, a dry chemical powder that has proven to be highly effective in LPG fire suppression. Sodium bicarbonate works on the principle of smothering the fire by generating carbon dioxide gas and producing a cooling effect [12].

1. Decomposition of Sodium Bicarbonate: Sodium bicarbonate decomposes when exposed to heat, releasing CO_2 gas.

Equation: $2NaHCO_{3(s)} \rightarrow 2Na_2CO_{3(s)} + 2H_2O_{(g)} + 2CO_{2(g)}$

Sodium bicarbonate, when applied to an LPG fire, releases carbon dioxide (CO_2) upon contact with heat. The CO_2 gas displaces oxygen, a critical element in the Fire Triangle, effectively reducing the oxygen concentration and inhibiting the combustion process.

2. Smothering Effect: The CO_2 gas generated during the decomposition of sodium bicarbonate displaces oxygen (O_2), reducing the concentration of oxygen available to support the combustion of LPG.

Equation: $2\ CO_{2(g)} + 2\ C_3H_{8(g)} + 10\ O_{2(g)} \rightarrow 6\ CO_{2(g)} + 8\ H_2O_{(g)}$

In this reaction, carbon dioxide (CO_2) generated from the baking soda combines with LPG (C_3H_8) and atmospheric oxygen (O_2) to form water vapor (H_2O) and carbon dioxide. This reaction contributes to the suppression of the fire by reducing the availability of oxygen. Simultaneously, sodium bicarbonate absorbs heat from the fire, further cooling the flames.

3. Cooling Effect: The reaction between CO_2 and the flames has a cooling effect, reducing the temperature of the fire.

- The cooling effect is a physical reaction, not a chemical one.

This dual-action mechanism of oxygen displacement and cooling makes sodium bicarbonate a potent suppression agent for LPG fires.

Another advantage of sodium bicarbonate is its non-conductive properties, which make it safe to use on electrical fires that may occur in LPG-related incidents. This characteristic adds to its versatility and practicality in industrial settings where LPG is employed [12].

2.1.5. Technology in Fire Detection and Suppression

Arduino, an open-source hardware and software platform, stands at the forefront of electronic system design and control. Renowned for its adaptability and versatility, Arduino microcontrollers play a pivotal role in modern fire suppression systems [13]. These microcontrollers are instrumental in monitoring sensors, processing crucial data, and initiating automated responses. By seamlessly integrating Arduino technology, fire suppression systems are endowed with intelligence and automation, which significantly enhance their efficiency and responsiveness. This enhancement, in turn, leads to quicker response times and improved overall effectiveness. Arduino empowers fire suppression systems to swiftly detect fire-related parameters, allowing for timely, automated decision-making and precise control [14].

The Internet of Things (IoT) represents a vast network of interconnected devices and sensors that communicate and exchange data via the internet [15]. In the realm of fire safety, IoT technology has found crucial application. Sensors and devices deployed in fire suppression systems collect real-time information concerning environmental conditions, fire dynamics, and potential hazards [16]. This wealth of data is transmitted to a centralized system, where it is processed and analyzed in real time. IoT technology excels in enabling remote monitoring and control of fire suppression systems, transcending geographical boundaries and ensuring the efficiency of critical processes. IoT's capability to provide timely alerts, real-time data analysis, and decision support is paramount. It bolsters the safety and reliability of fire suppression systems by delivering swift, data-driven responses, ensuring that potential fire hazards are detected and mitigated with the utmost precision and effectiveness. The implementation of IoT technology presents a promising frontier for optimizing fire safety, offering an intelligent and data-driven approach to fire suppression that holds the potential to save lives and protect property effectively [17].

2.2. Empirical Literature Review

2.2.1. LPG Fire Incidents and Damage Assessment

According to a report from The Times of India, in a recent event that occurred in Chalikkavattom on October 6, 2022, an individual named P K Sudhakaran suffered burn injuries due to a cooking LPG gas cylinder catching fire and subsequently exploding within his residence. The mishap unfolded as Sudhakaran attempted to relocate the cylinder when it ignited, resulting in burns to his hands. The situation could have escalated into a more severe tragedy, as the cylinder detonated shortly after being moved, causing damage to nearby homes' windows and an electric post. The Gandhinagar fire station swiftly responded to the incident and successfully extinguished the fire. This incident underscores the potential hazards associated with the use of liquefied petroleum gas (LPG), particularly concerning issues like gas leakage and the possibility of catastrophic accidents.

The fundamental cause of the accident was traced back to the connection of a new LPG cylinder and the ignition of the stove's burner. It is suspected that gas leakage occurred through the regulator, leading to the ignition of the fire and its subsequent spread to the cylinder. This occurrence highlights the critical importance of implementing robust safety measures and effective fire suppression systems, particularly in situations involving LPG usage [18].

2.2.2. Effectiveness of Existing Fire Suppression Systems and Use of Suppression Agents

High Expansion Foam LPG Fire Control

An empirical study on high expansion foam LPG fire control examined the system's effectiveness in managing LPG fires. It identified two key mechanisms for controlling fires involving ordinary flammable liquids:

- The foam blanket that reduces heat transfer, and
- The foam that suppresses the vaporization of the liquid, ultimately reducing the burning rate.

However, the study found that when applied to LPG pool fires, the system's performance becomes more complex due to the elevated temperature of the LPG, which increases vaporization and the burning rate.

One significant weakness of the high expansion foam LPG fire control system is its limited ability to handle exceptionally large fires. The study showed that the system failed to control the largest LPG fire test, where the foam application time significantly exceeded the predicted control time. Additionally, designing an ideal foam system that balances all three key mechanisms simultaneously is challenging.

Furthermore, the study underscores the absence of automation in the high expansion foam system. The lack of automation, including the integration of Arduino and IoT technology, hinders the real-time monitoring and control of the foam application. An automated system could provide crucial data on fire conditions and foam application rates, allowing for immediate adjustments in response to changing fire dynamics. This technological enhancement would address the system's weaknesses by optimizing foam application and control strategies, potentially improving its effectiveness in tackling LPG fires of varying sizes and complexities.

The study highlights the high expansion foam LPG fire control system's potential but underscores significant weaknesses in handling large fires and the absence of automation [19].

Dry Chemical LPG Fire Extinguishment

The empirical study on dry chemical LPG fire extinguishment examined the effectiveness of three dry chemical agents in controlling LPG (liquefied petroleum gas) fires. The study developed an equation to correlate extinguishment time with dry chemical application rate and burning rate.

$$t_e - t_m = \frac{K}{\left(\frac{A_r - CB_r}{B_r}\right)^a}$$

- t_e = extinguishment time, sec.
- t_m = minimum extinguishment time, sec.
- A_r = dry chemical application rate, 1b/ftL-sec.
- B_r = burning rate, in/min.
- a, K, C_r = constants.

The equation was based on several observations and assumptions, including the proportional relationship between application rate and burning rate, the existence of a minimum extinguishment time, and the presence of a minimum application rate below which extinguishment would not occur. The analysis considered successful extinguishment attempts using fixed nozzle systems on unobstructed fires.

One of the strengths of the dry chemical LPG fire extinguishment system, as observed in the study, is its effectiveness in controlling LPG fires. The results showed that at low application rates, urea-$KHCO_3$ was more effective than $KHCO_3$ and $NaHCO_3$. However, all these dry chemicals were found to be capable of effectively extinguishing LPG fires. This is a significant advantage when dealing with class B fires involving flammable liquids like LPG.

However, the study also revealed certain weaknesses in the dry chemical LPG fire extinguishment system. At higher application rates, there was little difference in extinguishment times among the three dry chemicals, indicating a limited efficacy at higher rates. Moreover, it was noted that LPG fires could re-establish themselves over previously extinguished areas, prolonging the extinguishment process. To address these weaknesses, there is a need for automation in the dry chemical application system. The integration of automation, such as Arduino and IoT technology, could improve the real-time monitoring and control of dry chemical application rates, enhancing the system's effectiveness in managing LPG fires of varying sizes and complexities.

This study on dry chemical LPG fire extinguishment demonstrates the efficacy of dry chemicals in controlling LPG fires. This system offers advantages for class B fire suppression. However, it also highlights the need for automation to address its weaknesses, particularly at higher application rates and in preventing re-establishment of fires over extinguished areas [19].

Automated FM200 Fire Suppression System

The study involving the automated FM200 Fire Suppression System demonstrates the effectiveness and advantages of an automated fire suppression system using FM-200 as the fire extinguishing agent. FM-200 is a colorless, odorless, electrically non-conductive vapor that leaves no residue and has acceptable toxicity for use in occupied spaces. This automated system is designed to provide swift fire suppression, reaching extinguishing levels in less than 10 seconds. It is safe for people in the protected area and maintains low extinguishing concentration, minimizing obstruction to vision during evacuation. Additionally, the system is environmentally friendly, with zero ozone depletion and global warming potential, making it a sustainable choice for fire protection. This system is embedded with a multitude of detectors, spray nozzles and extinguishing containments for automated intervention. **Figure 3** lays out a schematic of the FM200 system component design and functionality.

The results of this study emphasize the significant advantages of using an automated Fire Suppression System. Notably, the rapid response time of less than 10 seconds ensures that fires are suppressed swiftly, reducing the potential for damage and injury. The system's low extinguishing concentration and absence of residue make it suitable for occupied spaces and sensitive equipment,

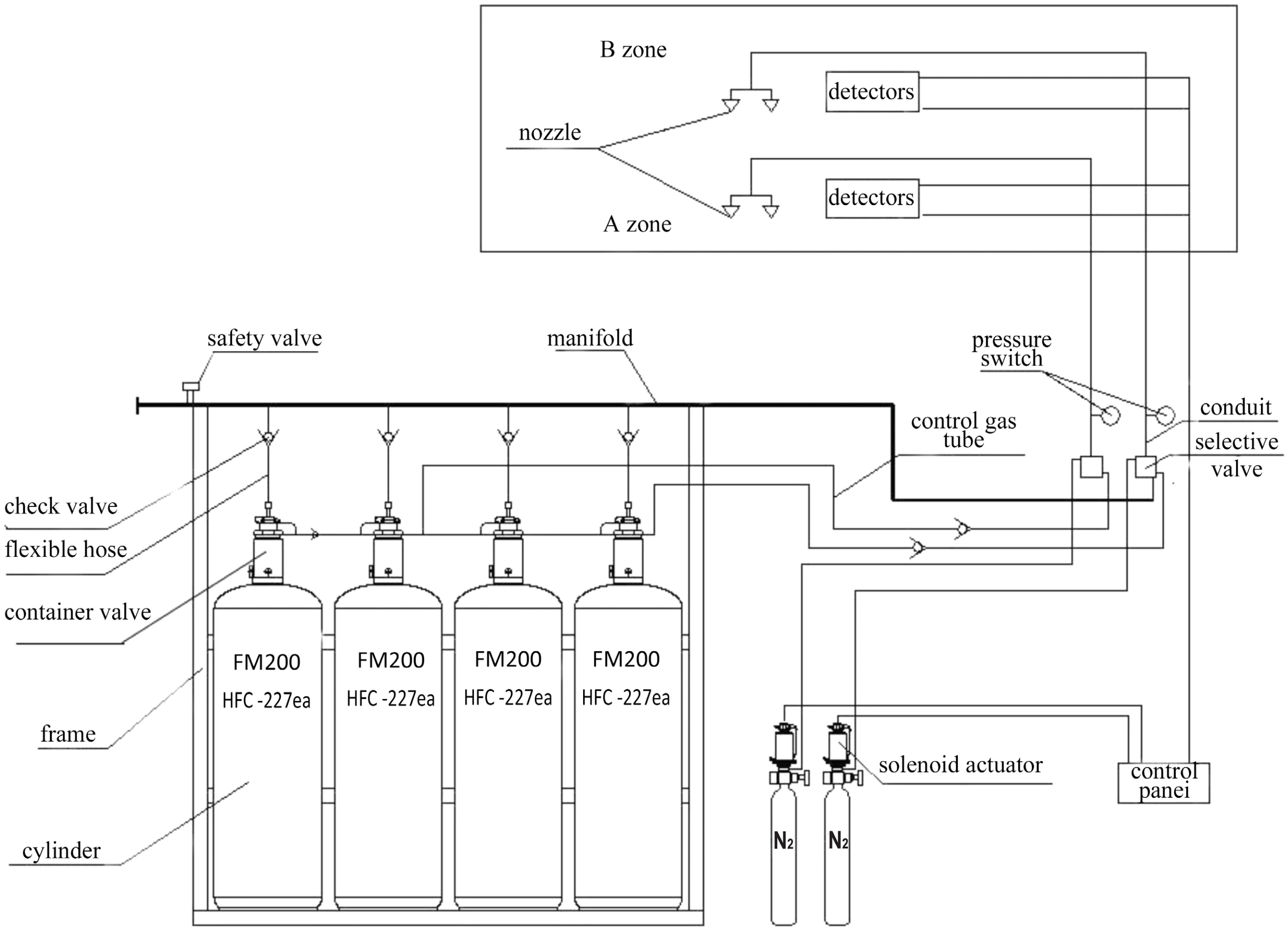

Figure 3. A schematic layout of an automated FM200 Fire suppression system.

as it minimizes disruptions and damage during and after a fire incident highlighting a need for suitable highly specific and environmentally friendly suppression agents of fire.

The integration of technology plays a pivotal role in enhancing the performance and control of fire suppression systems. Automated systems, like the FM200 tested, rely on advanced technology to detect fires, assess the situation, and trigger the release of fire suppressant agents. Integrating IoT (Internet of Things) technology, advanced sensors, and control systems, including Arduino-based solutions, can further improve the accuracy and efficiency of fire detection and suppression. These technologies allow for real-time monitoring, data analysis, and remote control, ensuring that the fire suppression system responds promptly and effectively to changing fire dynamics [20].

2.2.3. Performance Assessment Metrics and Key Performance Indicators (KPIs)

Evaluating the performance and reliability of fire suppression systems, especially in LPG fire scenarios, requires the definition and measurement of specific key performance indicators (KPIs).

Detection Accuracy, this is a critical KPI for automated fire suppression systems. It measures the system's ability to accurately identify the presence of a fire. From the context of the Automated FM200 Fire Suppression System, the KPI of detection accuracy assesses the precision with which the system recognizes fire-related conditions through the use of sensors, such as heat and smoke detectors. High detection accuracy is essential for triggering rapid response and minimizing the potential spread of the fire [20].

Response time is a fundamental KPI that gauges how quickly the fire suppression system reacts once a fire is detected. The Automated FM200 Fire Suppression System showcases a rapid response time, extinguishing fires in less than 10 seconds. This KPI underscores the importance of swift reaction to minimize damage and protect lives. IoT and Arduino technologies will play a pivotal role in enhancing response time by enabling real-time monitoring, immediate data analysis, and automated actions [20].

Suppression effectiveness is a central KPI that measures how efficiently a fire suppression system extinguishes fires and prevents re-ignition. As of High Expansion Foam LPG Fire Control, Dry Chemical LPG Fire Extinguishment, and the Automated FM200 Fire Suppression System, this KPI assesses the ability of each system to control and extinguish LPG fires. For example, the High Expansion Foam system demonstrates the successful control of LPG fires when applied at the appropriate rate. Measurement of this KPI is essential to ensure that the suppression system can effectively tackle different fire scenarios [19].

2.3. Summary of Literature Review

The information in the literature review was summarized in **Table 1**.

Table 1. A summary of the literature review.

Source	Summary of Information
Ukpaukure, Aimikhe, & Ojapah, 2023	Introduction to LPG Fire Safety: LPG is a versatile fuel source with applications in various industries. Safety in handling LPG is crucial to protect lives, property, and the environment. Effective safety measures and LPG fire suppression systems are essential.
WLPGA, 2018	Importance of LPG Safety: LPG safety is vital across industries, as mishandling can lead to fires, explosions, and environmental damage. Effective safety measures and LPG fire suppression systems are essential to mitigate these risks.
FSAC, 2022	Foundations of Fire Safety: The Fire Triangle and Tetrahedron theories underpin fire safety, emphasizing the role of fuel, oxygen, ignition sources, and chemical reactions. Understanding these theories is crucial for LPG fire safety.
Liang, et al., 2021	Unique Characteristics of LPG Fires: LPG fires are highly flammable, volatile, and have distinct vapor density properties. Effective safety measures and fire suppression strategies are necessary to manage these characteristics.
Ge & Wang, 2009	Chemical Reactions in LPG Fires: LPG fires involve vaporization and heat release, resulting in clean, nearly invisible flames. Early detection of LPG fires can be challenging due to the absence of visible smoke.
Haidar & Jagannadha, 2020	Sodium Bicarbonate as a Suppression Agent: Sodium bicarbonate is effective for LPG fire suppression due to oxygen displacement and cooling effects. Its non-conductive properties make it suitable for electrical fires.
Zlatanov, 2015	Arduino Technology: Arduino microcontrollers enhance fire suppression systems by monitoring sensors, processing data, and triggering automated responses, leading to quicker response times and improved efficiency.
Gillis, 2021	Internet of Things (IoT): IoT technology in fire safety enables real-time data collection and transmission, remote monitoring, and decision support. It enhances the safety and reliability of fire suppression systems.
Kochi, 2022	LPG Fire Incident: An incident highlights the potential hazards of LPG, including gas leakage and fire accidents. Robust safety measures and effective fire suppression systems are essential when using LPG.
ATC, 2011	High Expansion Foam LPG Fire Control: The study evaluates the effectiveness of high expansion foam in controlling LPG fires. It can suppress fires but has limitations in handling larger fires and lacks automation.
ATC, 2011	Dry Chemical LPG Fire Extinguishment: The study examines dry chemical agents for LPG fire control and highlights their effectiveness. However, these agents may have limitations at higher application rates and can struggle with re-establishment of fires.
Hangzhou Pri-Safety Fire Technology CO., 2018	Automated FM200 Fire Suppression System: The study demonstrates the advantages of an automated fire suppression system using FM-200 as the extinguishing agent. It highlights rapid response times, safety, and the need for technology integration.

3. Methodology

3.1. System Design and Conceptualization

This phase involved the development of a conceptual design for the ALPG-FSS. This design encompassed both hardware and software components, outlining their architecture and integration. The focus was on devising an efficient control algorithm that enables rapid fire control measures, ensuring the system's effectiveness in mitigating fire hazards.

3.1.1. Requirement Specifications

To initiate the design process, meticulous identification and definition of the ALPG-FSS requirements were paramount. These requirements encompassed various facets, including environmental conditions, potential fire scenarios, regulatory standards, and safety protocols.

The system was optimized for a wide temperature spectrum, ensuring reliability in diverse climatic conditions, the ALPG-FSS incorporated components rated for broader temperature tolerances, and humidity.

In a room, the ambient temperature typically ranges between 20˚C to 25˚C (68˚F to 77˚F). However, this varies basing on geographical location, building design, and room usage. For industrial settings or areas prone to higher temperatures, ambient room temperatures might range from 15˚C to 35˚C (59˚F to 95˚F) or even higher. On the other hand, humidity levels indoors typically range between 30% to 50% relative humidity. However, these levels fluctuate based on climate, ventilation, and activities within the room. The recommended ranges for operations based on environmental factors were summarized in Table 2.

Table 2. Normal and recommended ranges of Environmental factors.

Environmental Factor	Normal Range	Recommended Range for Component Operation
Moisture	30% - 50% RH	20% - 70% RH
Temperature	20˚C - 25˚C	−10˚C to 50˚C

In a typical cooking scenario using LPG, the flame intensity can vary. However, the standard flame intensity for a gas stove or burner used for cooking with LPG can range between 1000 and 10,000 watts. Therefore, a good threshold for a fire detection sensor in this context of potential fire incidents was within the range of 1000 to 3000 watts, as this encompassed the typical flame intensity range for cooking while remaining sensitive enough to detect anomalies or hazardous situations, such as a gas leak or uncontrolled fire, without triggering false alarms during normal cooking scenarios.

During a cooking process, the LPG concentration within the atmosphere is zero as all the gas released is combustible and in case of any leakage, any small concentration of gas within the environment will be detected and suitable enough to indicate a gas leakage. The recommended ranges for operations based on cooking conditions were summarized in Table 3.

Table 3. Normal and Recommended ranges during cooking.

Cooking Condition	Normal Range	Recommended Range for Component Operation
Flame	<1000 watts	1000 watts – 3000 watts
LPG	0 - 200 ppm	200 ppm – 10,000 ppm

Materials Selection

The structural materials were selected based on fire resistance, durability and suitability for housing electrical components. Aluminum casing was chosen for its high heat resistance and light weight properties to protect internal circuitry. Heat-resistant plastic was used for insulation purposes, preventing short circuits under extreme conditions.

The actuator components, including the blower fan, were selected for their rapid actuation speeds and compatibility with LPG suppression agents, ensuring efficient fire control.

3.1.2. System Components Design

The core components of the ALPG-FSS were meticulously outlined during this phase. These included an array of sensors, control units, and the suppression mechanism. Of utmost importance is the specification of sensor types and their detailed specifications to ensure precise detection of LPG leaks, temperature fluctuations, and fire indicators.

The sensors were chosen based on their ability to detect fire indicators, that is temperature, gas leaks and flames.

Flame Sensor (KY-026 Module)

This sensor module was designed to detect flames or fire sources within a given wavelength range of infrared radiations (IR). It operated on an input voltage of 3.3 V to 5 V and had a detection angle of 60 degrees. It typically consisted of an IR receiver, comparator, and digital output LED indicator (see Figure 4).

The KY-026 module typically detected the infrared spectrum emitted by flames. It focused on the characteristic wavelength of a fire, allowing it to distinguish flame presence. The module's sensitivity was adjusted through a potentiometer, enabling customization for various flame intensities. It provided a digital output signal, which changed when it detected flames, offering a quick and reliable indication of fire presence or intensity.

This module was incorporated to provide rapid detection of open flames, ensuring immediate response to fire outbreaks. The flame sensor was calibrated to detect infrared radiation within 760 - 1100 nm range, making it effective for recognizing fire at the different intensities.

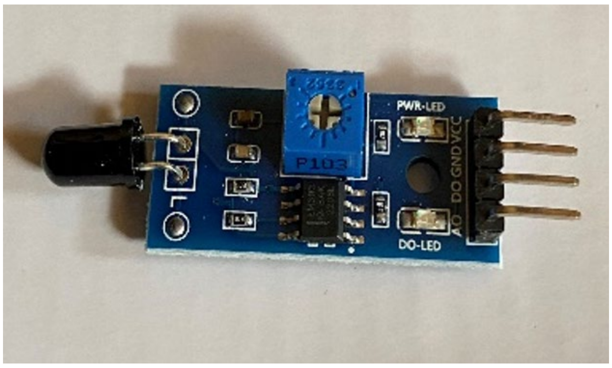

Figure 4. Flame sensor.

LPG Gas Sensor (MQ-2 Sensor)

The MQ-2 sensor module was designed to detect various gases, including LPG, butane, hydrogen, smoke, and other combustible gases. It operated on a voltage of about 5V and included a heating element and a gas-sensitive element, as shown in Figure 5.

The MQ-2 module employed a gas-sensitive element that changes its resistance when exposed to certain gases. It was calibrated to detect LPG gas within a concentration range. It was sensitive to the presence of LPG gas within the calibrated concentration, triggering an output signal when it reached the threshold.

The MQ-2 gas sensor was selected for detecting LPG leaks due to its high sensitivity to combustible gases. This module was calibrated within a gas concentration range of 200 – 10,000 ppm, which covers common LPG leak scenarios.

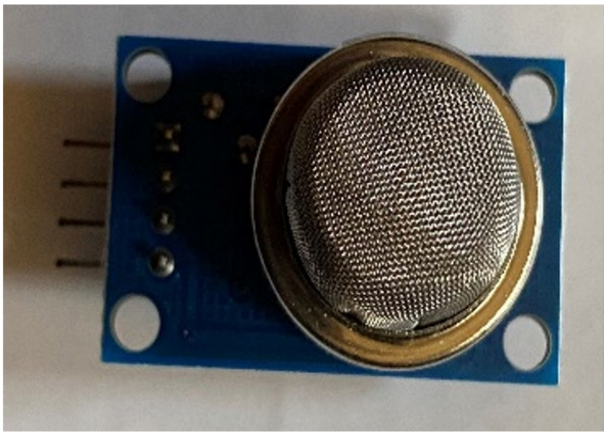

Figure 5. LPG gas sensor.

Temperature-Humidity Sensor (DHT11 Sensor)

This sensor was a combined module for measuring temperature and humidity. It typically operated on a 3.3V to 5V power supply and provided a digital signal output. It measured temperatures in the range of 0˚C to 50˚C with a humidity range of 20% to 90% RH.

The DHT11 sensor employed a calibrated digital signal output, providing accurate readings of temperature and humidity. It used a thermistor for temperature measurement and a humidity sensor for humidity measurements. Its accuracy varied slightly based on environmental conditions.

DHT11 temperature and humidity sensor was used to monitor the ambient

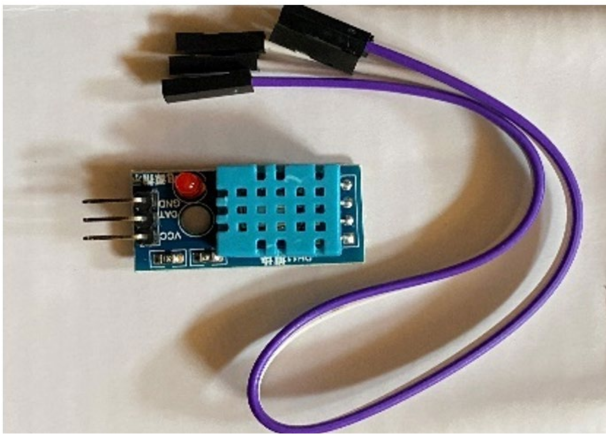

Figure 6. A DHT11 temperature + humidity sensor

conditions, ensuring that the system activates only under fire hazard conditions and was set to detect temperatures from −20 to 150 degrees Celsius, ensuring operation in both normal and extreme conditions. Figure 6 shows an illustration of components of the DHT11 sensor.

Seeeduino XIAO Development Board (SAMD21G18)

The Seeeduino XIAO is a microcontroller board based on the SAMD21 microchip. It operated at 3.3V and featured a Cortex-M0+ 32-bit ARM microcontroller. It included various interfaces such as I2C, SPI, UART, and a 12-bit ADC. It's compact as shown in Figure 7, which made it suitable for the project.

The SAMD21 microcontroller offered high performance and low power consumption, making it suitable for applications demanding efficiency. Its I2C, SPI, and UART interfaces facilitated communication with other devices and sensors. The 12-bit ADC ensured precise analog signal conversion. Its Cortex-M0+ architecture provided adequate processing power for handling data processing and system control tasks.

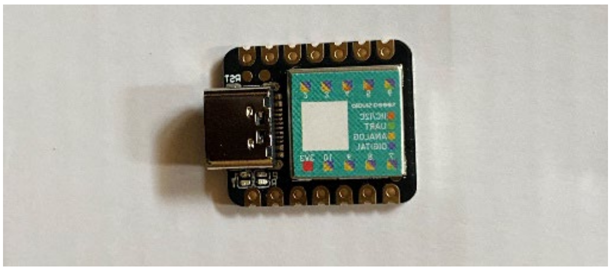

Figure 7. A Seeeduino XIAO SAMD21G18 development board.

Nano Controller

This Nano controller was based on the ATmega328P microcontroller and featured Mini USB connectivity options. It operated at 5 V and included a CH340 USB driver.

The ATmega328P microcontroller, running at 16 MHz, provided sufficient processing power for controlling various aspects of the ALPG-FSS system. Its USB connectivity options offered versatility in connecting to different devices for programming or data transfer. The CH340 USB driver ensured proper communication between the controller and the connected devices. The bootloader compatibility simplified the programming process, allowing for easy code uploads and updates.

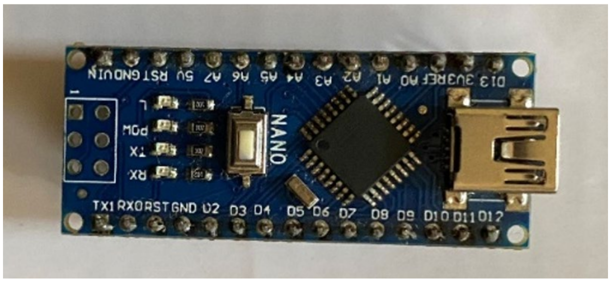

Figure 8. A Mini USB Nano 3.0 with bootloader compatible nano controller

Figure 8 illustrates a mini-USB nano 3.0 with bootloader compatible nano controller that was a channel for communication across the connected devices.

Display

This display was intended to showcase real-time temperature, humidity, and LPG levels. It operated on a communication protocol I2C (SCI.SDA) and used a serial interface. Typically, it operated at 5 V. Power requirements vary, usually within the range of 20 mA to 200 mA, depending on the display size and type. It was an OLED display (1 inch), see Figure 9. It employed a Control Interface/Protocol - I2C for communication with the controlling device.

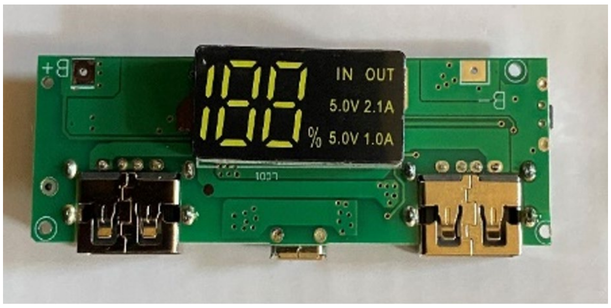

Figure 9. Display (GND VCC SCI.SDA Display).

Buzzer 85DB

This component served as the alarm system with an operational voltage of 5 V for a standard buzzer. Its power requirements typically ranged between 20 mA to 100 mA. It was controlled through direct voltage application and through a digital pin for turning it on/off. Figure 10 shows an illustration of the standard buzzer.

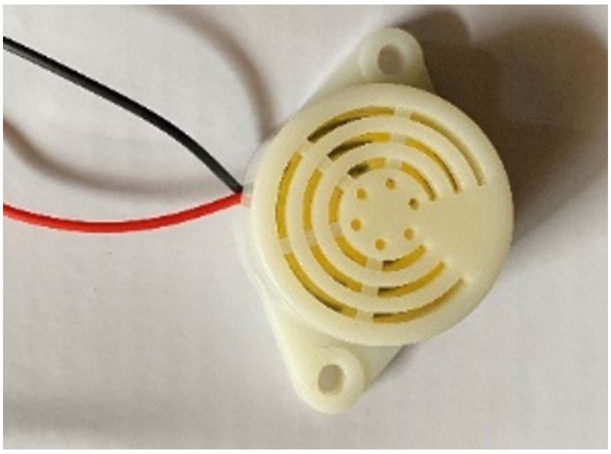

Figure 10. A Buzzer

Blower Fan (9733)

It was responsible for dispersing the sodium bicarbonate (suppression agent) over the fire. It had an operational voltage of 12 V - 24 V and power requirements of 100 mA to 500 mA, contingent on fan size and speed. Its dimensions were typically 97 mm × 33 mm, as shown in Figure 11.

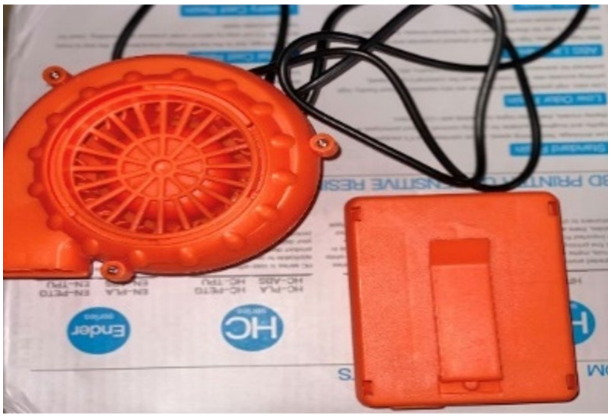

Figure 11. A 9733 Blower fan.

3.1.3. Schematic Layout of the System Design

The schematic layout of the Automated LPG Fire Suppression System (ALPG-FSS) was developed using Fritzing software and it embodied a comprehensive and interconnected infrastructure that orchestrated the system's functionality. At its core, this design delineated the intricate connections and interactions among the various hardware components, sensors, control units, and software modules. It mapped out the physical layout of the system, illustrating the relationships and pathways through which data flowed and actions were triggered. Each component's placement and interconnection were meticulously detailed, ensuring a cohesive and coherent system design.

All the sensors embedded on the system were interconnected to the control units and added to the hardware components, as illustrated by the schematic layout in Figure 12.

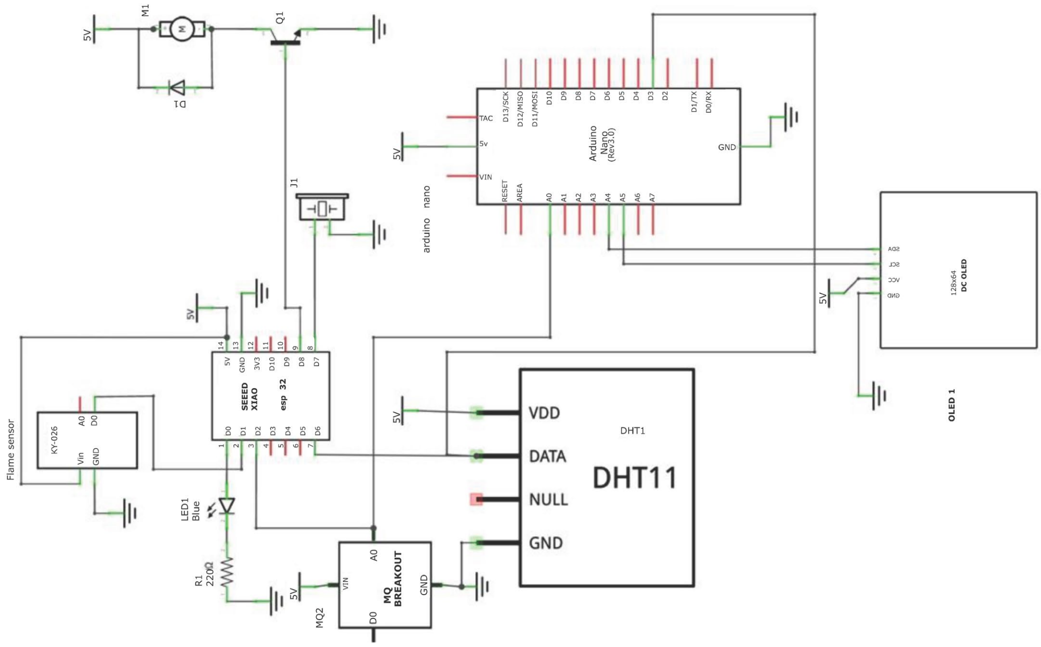

Figure 12. A Schematic layout of the automated LPG fire suppression system design.

3.2. Hardware Fabrication

Upon finalizing the design, the study proceeded to procurement of the necessary components and materials, including hardware from China through shipping. These components were assembled meticulously according to the design specifications. Rigorous testing of individual hardware modules followed to verify their functionality and reliability.

3.2.1. Component Assembly

The component assembly process involved the gathering and integration of various hardware elements essential for the ALPG-FSS. This phase included the physical realization of the detailed schematic illustrations. It encompassed the collection and placement of sensors, control units, and structural components essential for the system's functionality. The process prioritized precise connections, ensuring every element aligned with the designed specifications. Rigorous adherence to these assembly guidelines guaranteed the successful integration of each component, laying the foundation for the system's cohesive and functional hardware prototype.

3.2.2. Prototype Construction

It then proceeded with the physical construction of the ALPG-FSS prototype according to the detailed hardware design. It involved assembling the various components, ensuring proper connections and alignments as outlined in the design schematics.

The following components were used in fabricating the components of the system;

Soldering Solder Paste (RMA-223 - 10cc Flux), this particular flux was a critical element in the prototype construction process. Its function extended to ensuring optimal soldering connections between electronic components. **Figure 13** shows an illustration of soldering solder paste.

Figure 13. Soldering solder paste (RMA-223 - 10cc Flux).

PCB Board, the PCB (Printed Circuit Board), played a foundational role in the construction of the ALPG-FSS prototype. The selected 6 × 8CM PCB Board (see **Figure 14**) served as the structural base where various electronic components were mounted and interconnected. Its double-sided, universal DOT Perfboard design allowed for versatile placement and secure attachment of sensors and microcontrollers.

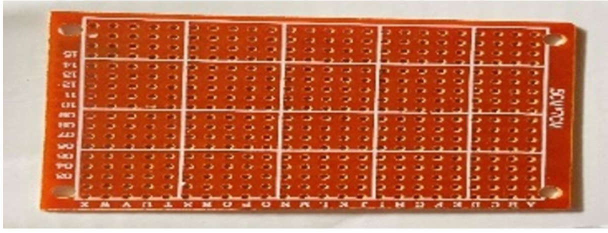

Figure 14. PCB Board.

Solder Wire (60 40 Rosin Core Tin Solder Wire, Diameter 1.5 - 2.0), this specific solder wire type, comprising a 60% tin and 40% lead composition, was an essential material utilized in the soldering process during prototype construction. Its rosin core ensured efficient and reliable soldering connections by reducing oxidation and promoting better adhesion between electronic components and the PCB board.

3.2.3. Sensor Integration and Calibration Ranges

The LPG Gas Sensor sensor's optimal performance for detecting LPG gas involved a concentration range of 200 to 10,000 ppm (parts per million). Calibration within this range ensured accurate detection and timely response to varying LPG gas concentrations.

The DHT11 sensor operated optimally within a temperature range of 0 to 50 degrees Celsius, ensuring accurate temperature readings for fire detection and environmental monitoring, whereas its optimal humidity range was between 20% to 80% relative humidity, allowing precise humidity measurements necessary for comprehensive environmental monitoring within the system.

The flame sensor's effectiveness was within a defined range of flame intensity levels typically observed during LPG combustion. For accurate detection, it operated optimally within a range corresponding to moderate to high flame intensities, often found in cooking scenarios with LPG.

3.2.4. Integration and Connectivity

The sensors were connected to the control units and communication networks in strict adherence to the design specifications. This integration involved establishing appropriate electrical connections, ensuring correct polarity, and aligning signal pins as outlined in the system's schematics. Each sensor was interfaced with the control units via designated input/output ports to enable data transmission and reception.

The control units were designed to receive sensor inputs, process the received data, and execute predetermined actions based on the established thresholds or trigger conditions. Communication protocol, I2C interface, were employed to facilitate seamless communication between the sensors and the control units, enabling real-time data transmission and response generation within the ALPG-FSS. This integration ensured the sensors' accurate readings and their effective contribution to the system's overall functionality and responsiveness.

3.2.5. Structural Implementation

Structural elements were fabricated to house and support the ALPG-FSS components. This involved constructing a wooden casing, mounting wooden brackets and enclosures necessary for the system's deployment and protection. Using plywood for the casing, brackets, and enclosures within the ALPG-FSS offered several advantages due to its robustness, cost-effectiveness, and ease of customization.

3.3 Software Development

During the software development phase, a robust codebase was crafted using the C++ programming language to drive the core functionality of the automated LPG fire suppression system (ALPG-FSS). This code served as the foundation for fire hazard detection and control, ensuring efficient and precise responses to potential threats. Additionally, it facilitated seamless integration with hardware components, guaranteeing a harmonious and synchronized operation of the ALPG-FSS. Notably, the software featured capacity to enable remote monitoring and control, thereby providing real-time intervention capabilities when required.

3.3.1. Software Architecture Design

The software architecture for the Automated LPG Fire Suppression System (ALPG-FSS) was designed to harmonize with the specified hardware specifications and control requirements. It was structured to integrate multiple software modules essential for seamless system operation, encompassing sensor interfacing, data processing, decision-making algorithms, and control mechanisms.

Sensor Interfacing Module, was designed to facilitate communication between the hardware sensors and the software system. The data processing module encompassed algorithms tailored to handle the incoming sensor data efficiently. Decision-Making Algorithms formed the core intelligence of the software system. The control mechanisms served as the operational interface between the software and the hardware components.

3.3.2. Programming and Coding

This phase involved programming and coding for the Automated LPG Fire Suppression System (ALPG-FSS), the focus was on leveraging Arduino-based systems and IoT technology, using the C++ programming language to develop robust software modules. Utilizing Arduino-based systems involved writing efficient and optimized code tailored to interact with the hardware components effectively. C++ was the primary programming language for this task, known for its versatility and suitability for embedded systems.

For sensor data processing, the software employed algorithms capable of interpreting incoming data streams from various sensors, including those detecting LPG concentration, temperature fluctuations, humidity levels, and flame detection. The implementation of fire detection algorithms involved writing sophisticated code that analyzed processed sensor data to identify potential fire hazards.

3.3.3. Integration of IoT (Internet of Things) Technology

This integration in the Automated LPG Fire Suppression System (ALPG-FSS) involved establishing a sophisticated network that facilitated seamless communication and data exchange among the system's various components. This integration aimed to enable real-time monitoring, analysis, and responsive actions based on the transmitted sensor data.

The IoT framework was leveraged to create protocols and mechanisms allowing for the collection, transmission, and aggregation of sensor data. This involved the development of communication protocols that ensure reliable and efficient data exchange between the sensors, control units, and a centralized monitoring system. MQTT (Message Queuing Telemetry Transport) was employed to facilitate data transmission over network connections. The centralized monitoring system served as a hub for receiving and analyzing sensor data in real time.

3.3.4. Real-Time Monitoring and Control

This played pivotal role in allowing for immediate response to detected fire indicators and continuous monitoring of system status. The implementation involved software programming to enable these functionalities, coupled with the integration of the Blynk mobile application for seamless real-time monitoring on mobile devices.

Real-time Sensor Data Monitoring, the software was programmed to continuously gather data from the integrated sensors, including LPG gas concentration, temperature, humidity, and flame detection. Autonomous Response Mechanisms, upon detecting fire indicators meeting the predefined criteria, the software-controlled algorithms activated the system's response mechanisms autonomous. The Blynk mobile application served as an interface for real-time monitoring of the ALPG-FSS.

3.4. System Testing and Evaluation

In the rigorous phase of system testing and evaluation, a multifaceted approach was undertaken to assess the performance and efficacy of the Automated LPG Fire Suppression System (ALPG-FSS).

3.4.1. Detection Accuracy

It involved subjecting the ALPG-FSS to controlled test scenarios replicating various fire indicators. This included controlled LPG leakages, controlled temperature changes and flame generation within a controlled environment. The system's ability to accurately detect and differentiate between these indicators was observed and quantified, often using statistical methods to measure true positives, false positives, true negatives, and false negatives.

3.4.2. Response Time

In assessing response time, a series of timed tests were conducted, initiating from the detection of fire indicators to the activation of the suppression mechanism. This process involved measuring and analyzing the system's latency in processing sensor data, making decisions based on predefined criteria, and initiating the response action. It included a detailed breakdown of the time taken at each stage to identify potential bottlenecks or areas for improvement.

3.4.3. Suppression Efficiency

Suppression efficiency evaluation typically comprised of controlled fire scenarios where the system's suppression mechanism was activated upon detection. This assessment measured the time taken to suppress the fire, the volume of the suppression agent used, the area covered by the suppression, and the effectiveness in extinguishing the fire. Post-suppression analysis also included assessing any residual fire or potential re-ignition points to ensure comprehensive fire containment.

3.4.4. Design of Controlled Test Scenarios

To evaluate the performance of the Automated LPG Fire Suppression System (ALPG-FSS), controlled test scenarios were carefully designed to simulate real-world LPG fire incidents. The key parameters considered in designing these scenarios included fire intensity, room size, and system activation conditions.

Fire Intensity: Fire intensity was varied by controlling the amount of LPG released before ignition. For consistency, predefined LPG volumes were used in each test, ensuring a repeatable and measurable fire intensity for each trial.

Room Size: The tests were conducted in a confined space measuring 3 m × 3 m × 3 m, which represents a typical kitchen or small industrial storage room where LPG leaks and fires are most likely to occur. The enclosure ensured a controlled environment where external factors such as wind or airflow variations were minimized.

System Activation Conditions: The ALPG-FSS was tested at different distances from the ignition source (0.5 m, 1 m, 1.5 m, and 2 m) to determine its response effectiveness. The system was triggered upon detecting temperature rise and gas concentration exceeding set threshold values.

Safety Measures: All tests were conducted in a controlled setting with fire extinguishers and ventilation measures in place to prevent uncontrolled fire spread. Personnel were stationed at a safe distance, and all safety protocols were strictly followed.

3.4.5. System Handling of False Alarms

During detection trials, the system was evaluated for its susceptibility to false positives (unwarranted activation) and false negatives (failure to detect a fire event). False positives can occur due to non-fire heat sources, high ambient temperatures, or sensor malfunctions, while false negatives may result from sensor insensitivity, obstruction, or delayed response times.

To mitigate false positives, the system incorporates a multi-sensor approach, where both a gas sensor (for detecting LPG leaks) and a temperature sensor (for heat detection) must register critical threshold values before activation. This dual verification minimizes cases where non-hazardous heat sources trigger an unnecessary response. Additionally, threshold values for temperature and gas concentration were carefully calibrated based on controlled test conditions to align with real fire scenarios.

To address false negatives, sensor placement was optimized to ensure maximum coverage of the fire-prone area, and periodic sensor calibration was conducted to maintain accuracy.

3.5. Analysis and Conclusion

The analysis phase involved a thorough examination of the data acquired from the system testing and evaluation processes. By correlating the results obtained from detection accuracy, response time, and suppression efficiency, a comprehensive understanding of the system performance was derived.

Drawing from the collected data, the analysis phase aimed to discern patterns, trends, and potential correlations. It involved identifying strengths and weaknesses in the system's performance across different parameters. It assessed whether the system demonstrated consistent detection accuracy across various fire indicators or if there were specific scenarios where its performance fluctuated. It also scrutinized how response time influenced the overall efficiency of fire containment and the suppression mechanism's effectiveness in diverse fire intensities. Based on these analyses, a conclusive summary was drawn during the final phase.

4. Results and Discussion

In this chapter, the empirical outcomes derived from rigorous experiments evaluating the Automated LPG Fire Suppression System (ALPG-FSS) are presented. These results, stemming from detection accuracy tests, response time analyses, and suppression efficiency evaluations, offer comprehensive insights into the system's performance. Through precise measurements and observations, this section elucidates the ALPG-FSS's capabilities in fire detection, response, and mitigation, laying the groundwork for informed discussions and conclusions.

4.1. Detection Accuracy Test Results

The detection accuracy tests assessed the sensor's responsiveness to varying LPG concentrations and Constant fire intensity across different distances from the prototype, as summarized in Table 4.

Table 4. Detection accuracy test table.

Detection Accuracy Test Table				
Test Scenario	**Distance (m)**	**Sensor Reading (%)**	**LPG Detection Time (s)**	**Fire Detection Time (s)**
1	0.5	98	2.87	6.51
2	1.0	79	4.37	10.06
3	1.5	73	5.21	14.79
4	2.0	67	6.79	-

Experimental Setup:

Distances Tested: 0.5 m, 1 m, 1.5 m, and 2 m from the system.

Concentrations Used: Varying LPG concentrations at each distance.

Flame Used: Constant Flame Intensity.

4.1.1. Variation of LPG Detection Time against Distance from the System

The results from the LPG detection accuracy tests conducted at various distances—0.5 m, 1 m, 1.5 m, and 2 m—from the system yielded insightful trends. As the distance increased, there was a noticeable elongation in the detection time. At 0.5 m, the system exhibited a swift response time, detecting the presence of LPG within an average of 2.87 seconds. However, as the distance expanded to 2 m, the detection time extended to 6.79 seconds, showing a significant delay in sensing LPG presence. This consistent elongation in detection time with increased distance indicates a direct relationship between proximity and the system's ability to promptly detect LPG leaks.

Figure 15 shows the relationship between LPG detection time of the system at different distances away from the ignition source.

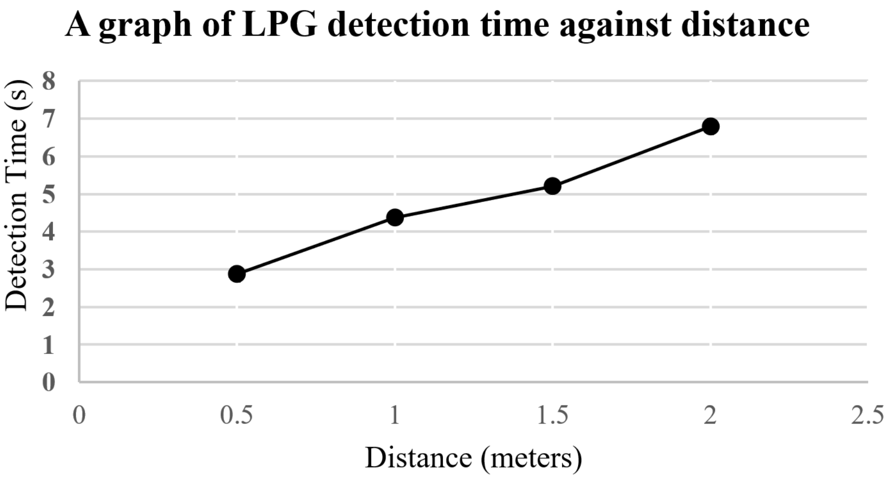

Figure 15. A Graph of Variation of LPG detection time with increasing distance.

The plotted line graph further emphasizes this relationship between distance and detection time. A clear positive correlation is depicted, where the detection time steadily rises as the distance from the system increases. The graph's trend line illustrates a linear increase in detection time, affirming the inverse proportionality between proximity and detection speed. This consistent pattern aligns with the system's expected behavior, confirming that the system's efficiency in LPG detection is inversely affected by distance due to decrease in concentration of the gas molecules reaching the sensors to be detected at increased distance and hence increased detection time.

4.1.2. Variation in Fire Detection Time against Distance from the System

The fire detection accuracy test at varying distances—0.5 m, 1 m, 1.5 m, and 2 m—from the system showcased an intriguing trend in detection time. The recorded detection times displayed a discernible increase as the distance from the system expanded. At 0.5 m, the sensor's response time was 6.51 s, which surged to 10.06 s at 1m and further increased to 14.79 s at 1.5 m. Notably, no fire detection was registered at 2 m. This trend illustrates a significant relationship between distance and the sensor's response time, depicting a prolonged detection period with increased distance, culminating in a failure to detect fire at the furthest distance. The relationship between fire detection time of the system at different distances away from the ignition source is shown in Figure 16.

A graph of fire detection time against distance

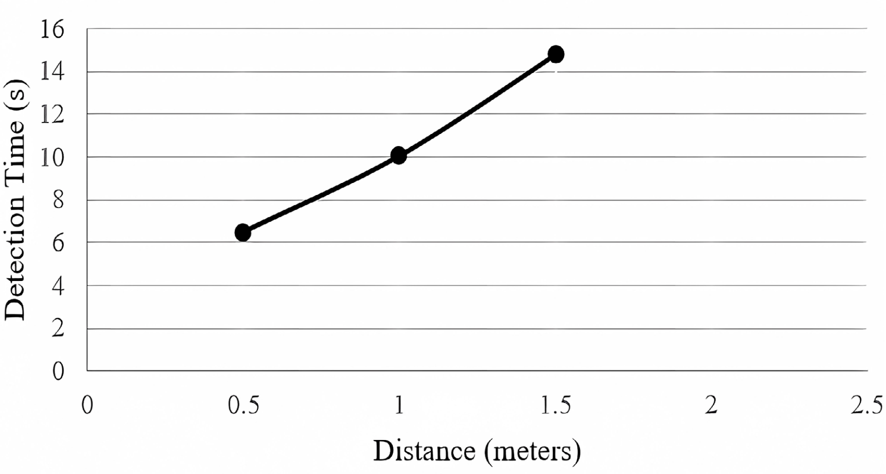

Figure 16. A Graph of Variation of fire detection time with increasing distance.

The line graph representation of these findings exhibits the correlation between distance and fire detection time. A clear upward trend in detection time is evident as the distance from the system escalates. The graph delineates a steady rise in detection time, corroborating the inverse relationship between distance and the sensor's efficiency in detecting fire occurrences. Moreover, the graph displays a distinct cutoff point at 2 m, indicating the point at which the sensor ceases to detect fire, reinforcing the critical impact of distance on the sensor's functionality. This is attributed to diminishing strength of infrared radiations from the flame at increased distance leading to increased detection periods by sensors.

4.2. Response Time Test Results

The Response Time Tests gauged the sensor's swiftness in detecting LPG and fire by delving into the time taken by sensors to identify alterations, crucial for assessing promptness and reliability. Table 5 summarizes the response times of the system at different distances.

Experimental Setup:

Distances Tested: 0.5 m, 1 m, 1.5 m, and 2 m from the system.

Concentrations Used: Varying LPG concentrations at each distance.

Flame Used: Constant Flame Intensity.

Table 5. Response time test table.

Response Time Test Table				
			Detection Time (s)	
Test Scenario	**Distance (m)**	**Sensor Reading (%)**	**LPG Average Time**	**Fire Average Time**
1	0.5	97	2.54	8.32
2	1.0	82	4.11	10.85
3	1.5	76	5.04	14.19
4	2.0	69	6.83	-

4.2.1. Variation of Response Time to LPG against Distance from the System

The recorded response times for LPG detection at varying distances—0.5 m, 1 m, 1.5 m, and 2 m—from the system demonstrate a notable increase in response time with greater distances. At 0.5 m, the average response time across three tests was 2.54 s, which increased to 4.11s at 1 m, further climbing to 5.04 s at 1.5 m, and notably elevated to 6.83 s at 2 m. These results exhibit a consistent escalation in response time as the distance from the system expands, highlighting a distinct relationship between distance and the sensor's efficiency in detecting LPG concentrations, see **Figure 17**.

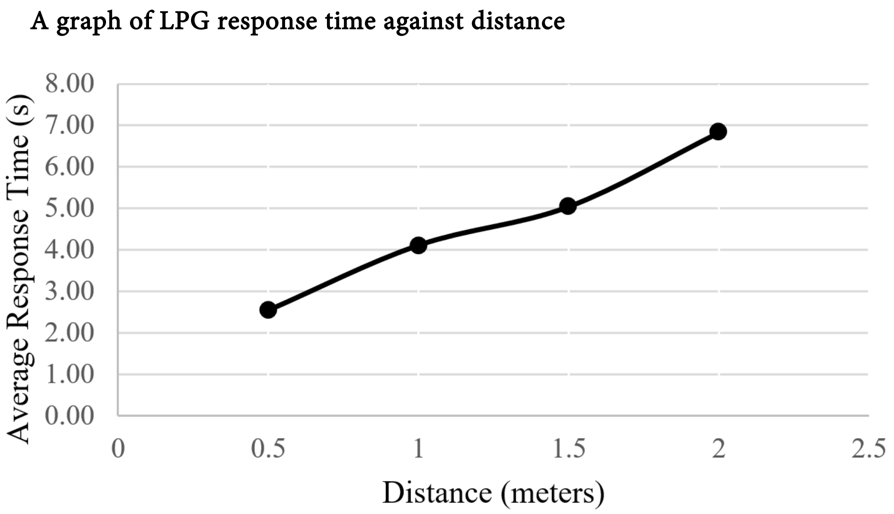

Figure 17. A Graph of System Average Response Time to LPG.

The increase in response time of LPG sensors with greater distance aligns with the principles of gas dispersion. As distance extends, gas molecules disperse further, reducing concentration levels. The sensor needs time to detect and accumulate sufficient gas particles for accurate readings. At closer distances, higher gas concentrations facilitate quicker sensor response due to immediate exposure. With distance, lower gas concentration delays sensor reaction, demanding additional time to collect adequate gas particles for detection, inherently elongating response time.

4.2.2. Variation of Response Time to Fire against Distance from the System

The recorded response times for fire detection demonstrate a trend. At 0.5 m, the average response time across three tests was 8.32 s, which increased slightly to 10.85 s at 1 m. Moving further to 1.5 m, the average response time further extended to 14.19 s, showcasing a clear progression in response time with increased distance from the source.

These findings indicate a noticeable rise in response time as the distance from the fire increases, revealing a correlation between distance and the sensor's efficiency in detecting fire. Figure 18 illustrates the relationship between LPG response time and distance from the system.

A graph of LPG response time against distance

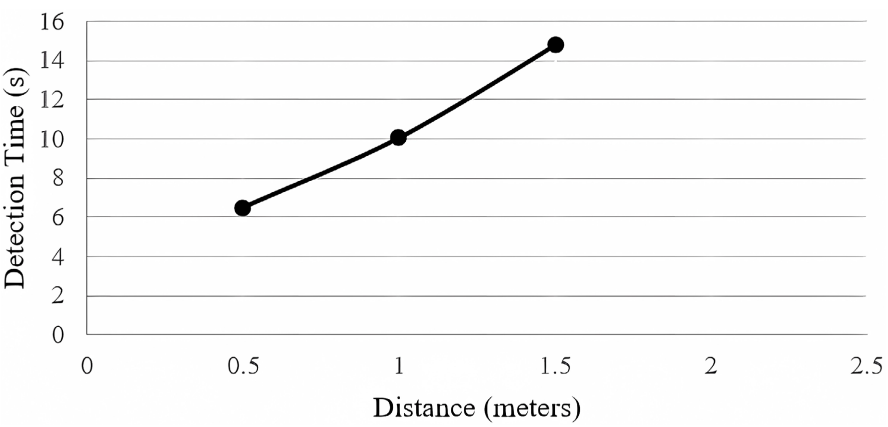

Figure 18. A Graph of Variation of fire detection time with increasing distance.

The increase in fire response time with greater distance aligns with the inverse square law of physics. As distance expands, the energy from the fire source disperses across a larger area, resulting in reduced energy intensity at the sensor location. This reduction necessitates longer time for the sensor to register the diminished energy levels, hence elongating the response time.

4.3. Suppression Efficiency Test Results

The Suppression Efficiency tests aimed to assess the system's effectiveness with the use of sodium bicarbonate as a fire suppression agent, examining its extinguishing capabilities at varying distances from the prototype under controlled flame intensities. Table 6 summarizes the efficiency of fire suppression of the system at different distances in terms of extinguishing extent.

Experimental Setup:

Distances Tested: 0.5 m, 1 m, 1.5 m, and 2 m from the system.

Flame Used: Constant Flame Intensity.

Quantity of Sodium Bicarbonate Used: 25 g.

4.3.1. Variation of Fire Suppression Efficiency at Different Distances

The fire suppression efficiency tests with sodium bicarbonate revealed varying results based on distance from the system. At closer distances of 0.5 m and 1m, the

Table 6. Fire suppression efficiency test table.

Fire Suppression Efficiency Test Table				
Test Scenario	**Distance (m)**	**Blower Status (On/Off)**	**Suppression Time (s)**	**Extinguishing Extent**
1	0.5	On	10.45	Complete
2	1.0	On	14.21	Complete
3	1.5	On	21.7	Diminishing Flame
4	2.0	Off	-	No extinguishing

suppression time was recorded as 10.45 s and 14.21 s, respectively. However, as the distance increased to 1.5 m, the suppression time notably extended to 21.7 s.

This trend aligns with the physical limitations of the suppression agent's dispersion capability, which could effectively address fires in closer proximity but demonstrated reduced efficiency at greater distances. The absence of suppression at 2 m, correlated with the lack of fire detection, further emphasizes the direct relationship between detection range and suppression efficiency.

The relationship between fire suppression time of the system and distance is illustrated in **Figure 19**.

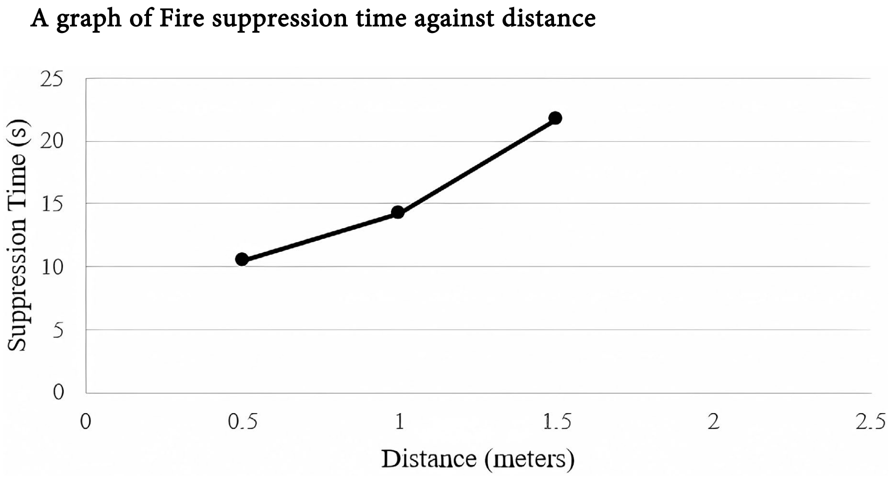

Figure 19. A graph of variation of fire suppression time against distance.

The line graph depicting the variation showcases a noticeable increase in suppression time with increasing distance, highlighting the agent's limitations in reaching and effectively suppressing fires at extended distances. This trend underscores the critical role of proximity in achieving efficient fire suppression using sodium bicarbonate, emphasizing its suitability for closer fire events within its operational range.

4.3.2. Effectiveness of Sodium Bicarbonate as Suppression Agent

The observed variation in flame suppression with sodium bicarbonate aligns with its mechanism of action and dispersion limitations. At closer distances of 0.5 m and 1 m, where complete extinguishing was observed, the sodium bicarbonate had sufficient proximity to effectively smother and suppress the flame. As the distance increased to 1.5 m, the suppression effectiveness reduced, leading to a diminishing flame and partial extinguishing. This decline is attributed to the dispersal characteristics of sodium bicarbonate; while it can effectively combat fires in proximity, its coverage and dispersal capabilities lessen with distance. At 2 m, where no flame detection occurred, no suppression was observed, consistent with the absence of a fire event for the agent to act upon.

Sodium bicarbonate operates as a suppression agent primarily through the release of carbon dioxide upon thermal decomposition, thereby smothering the fire by displacing oxygen. However, its effectiveness diminishes with increased distance due to dispersion limitations. Its capability to entirely suppress flames at closer ranges demonstrates its potential as an effective suppression agent for LPG fires within its operational range. However, beyond a certain distance, the dispersion limitations reduce its effectiveness, as seen in the diminishing suppression capability at 1.5 m and the absence of action at 2 m, where no fire was detected. This underscores the critical influence of proximity on the agent's efficiency, emphasizing its suitability for addressing fires within a limited operational distance.

Comparison between sodium bicarbonate and other suppression agents

Sodium bicarbonate was chosen as the fire suppression agent in this system due to key factors, including its cost-effectiveness, environmental impact, and suitability for LPG fires. While FM-200 is known for its rapid suppression and clean discharge, it is significantly more expensive and requires pressurized storage, making it less practical for widespread deployment in cost-sensitive applications such as domestic kitchens, small-scale industrial settings, and mobile LPG storage units.

Sodium bicarbonate also works by releasing carbon dioxide upon decomposition, which helps to smother the fire while also interrupting the chemical chain reaction. It is non-toxic, widely available, and does not deplete oxygen levels, making it safer for enclosed spaces where occupants may still be present during suppression. In contrast, FM-200 relies on a chemical gas discharge system, which, while effective, requires specialized equipment and trained personnel for handling and refilling.

Additionally, while FM-200 leaves no residue, sodium bicarbonate's minimal residue is easy to clean and does not cause damage to electrical components or surfaces, unlike some alternative dry chemical agents. Given these considerations, sodium bicarbonate provided a balance between efficiency, affordability, and practicality, making it an optimal choice for an automated LPG fire suppression system aimed at cost-effective and accessible fire safety solutions.

4.3.3. Comparison of the Automated LPG Fire Suppression System to Existing Fire Safety Measures

- Based on Reaction Times

The ALPG-FSS and the High Expansion Foam (HEF) LPG Fire Control system differ significantly in their automation and manual handling. The ALPG-FSS leans towards more automated fire suppression, swiftly responding to fire indicators autonomously, requiring minimal human intervention for activation. This autonomous behavior contributes to its quick reaction time towards fire suppression, allowing for rapid mitigation.

Conversely, the HEF LPG Fire Control, while automated in its dispersal process, requires more manual handling during setup and deployment due to the nature of foam application. Its reaction time might be slightly slower than the ALPG-FSS due to the need for deployment and expansion.

Additionally, the Automated FM200 Fire Suppression System operates predominantly in an automated mode, reacting swiftly to fire indications with minimal manual intervention, similar to the ALPG-FSS. Its reaction time is relatively fast, offering efficient fire suppression within a short timeframe.

Based on the comparison of reaction times of the different fire suppression systems, the APG-FSS and FM200 have a better yet equal reaction time as compared to high expansion foam LPG fire control, see **Figure 20**.

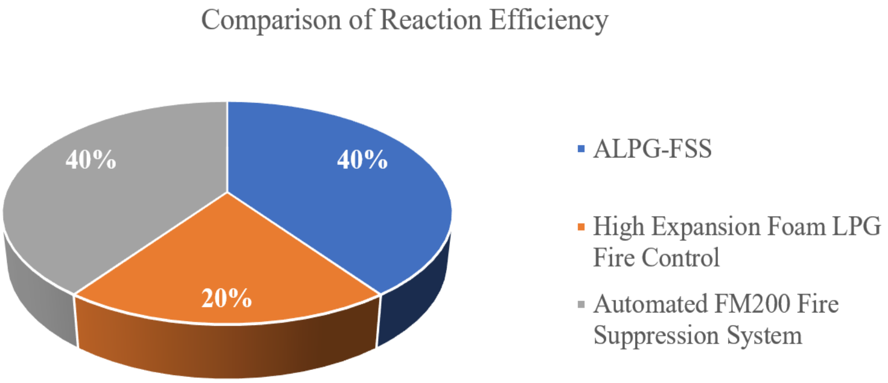

Figure 20. Pie Chart comparing percentage efficiency of fire suppression systems (Based on Reaction time).

Quantifying these aspects in terms of reaction time and automation, the ALPG-FSS and Automated FM200 each contribute 40% to the overall automation and reaction speed due to their predominantly automated operation. The HEF LPG Fire Control, although automated in dispersal, requires more manual handling during setup, accounting for 20% in the comparison. This division represents the varying degrees of automation and reaction times among the systems.

- Based on Extent of Fire Suppression

The ALPG-FSS, utilizing sodium bicarbonate, showcases remarkable efficacy in close-range fire control, achieving complete extinguishing at 0.5 m and 1 m distances and partial suppression at 1.5 m, covering approximately 66.7% of the tested operational range. Conversely, the High Expansion Foam (HEF) LPG Fire Control system is renowned for expansive coverage, excelling in larger areas and potentially addressing a broader spectrum of fire scenarios. Quantitatively, the ALPG-FSS demonstrates about 66.7% effectiveness within the tested operational range, while the HEF system potentially covers a broader range of fire scenarios in larger spaces, possibly more than the ALPG-FSS in those specific scenarios.

5. Conclusions and Recommendations

This chapter synthesizes insights based on the findings, offering crucial recommendations for enhancing the ALPG-FSS and future research directions.

5.1. Conclusions

The conclusions stem from comprehensive analyses of empirical data, observations, and performance evaluations within diverse experimental settings:

1. The ALPG-FSS's exceptional fire suppression performance at closer distances, achieving complete extinguishing at 0.5 m and substantial suppression at 1 m, highlights its remarkable suitability for confined spaces or situations requiring rapid and accurate fire control. This is indicative of its precise response capability, effectively covering around 66.7% of the tested operational range. The system's ability to swiftly and effectively address immediate threats underscores its potential for scenarios where precision and swift action are crucial, such as indoor environments or smaller enclosures.
2. The observable decline in the ALPG-FSS's performance as the distance increases beyond the 1.5 m threshold is a key finding. This is manifested through notable reductions in both detection accuracy and response time for both LPG and fire incidents. The decreasing accuracy and delayed response time beyond this threshold highlight a notable limitation of the system in effectively covering larger spatial areas. These limitations emphasize the need for supplementary or alternative measures, especially in extensive environments or scenarios demanding coverage beyond its operational range.
3. The evident efficacy of sodium bicarbonate as a suppression agent is noteworthy, particularly in its immediate fire control capabilities at shorter distances. The agent's ability to achieve complete extinguishing at 0.5 m and considerable suppression even at 1.5 m distances accentuates its potential for swiftly containing fire outbreaks. However, the diminishing effect observed at 1.5 m suggests that its efficiency is distance-dependent. While highly effective in immediate fire control scenarios, its performance diminishes as the distance from the source increases, indicating the need for supplementary strategies for more extensive coverage areas.
4. The ALPG-FSS and High Expansion Foam (HEF) LPG Fire Control systems offer distinct advantages based on their operational scopes. The ALPG-FSS showcases a more targeted and precise approach, best suited for environments necessitating immediate and localized fire suppression. This system performs remarkably well within confined spaces or scenarios demanding prompt and accurate fire control, covering about 66.7% of the tested range. Contrastingly, HEF presents a broader spectrum of coverage, catering to larger areas and potentially addressing a wider array of fire scenarios. Its expansive reach implies its suitability for extensive spaces or scenarios where comprehensive coverage is essential, possibly surpassing the ALPG-FSS in those specific situations. This comparison emphasizes the importance of selecting the appropriate system

based on spatial considerations and the specific demands of the environment.

5. The research findings underscore critical factors influencing the selection and deployment of fire suppression systems in real-world scenarios. The ALPG-FSS, with its emphasis on immediate and precise fire control within a limited operational range, proves advantageous for environments requiring close-range precision, such as confined indoor spaces or critical equipment installations. The system's proficiency in rapid response and focused suppression aligns with scenarios where containment and swift action are paramount.

5.2. Recommendations

- Refine sensor calibration and response algorithms to optimize the system's precision.
- Develop adaptable configuration designs to extend the ALPG-FSS's coverage while maintaining precision, enabling its use in diverse spatial settings.
- Investigate the ALPG-FSS's performance in varied environmental conditions to ensure consistent efficacy across humidity, temperature, and airflow changes.
- Assess the compatibility and synergy of multiple fire suppression systems, including the ALPG-FSS for comprehensive fire safety solutions.
- Undertake extended durability assessments to ensure the ALPG-FSS's consistent functionality and identify potential wear issues over time.

Patent

Uganda Registration Services Bureau (URSB), Patent Number [UG/P/2024/13].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations

LPG	Liquefied Petroleum Gas
ALPG-FSS	Automated LPG Fire Suppression System
HEF	High Expansion Foam
IoT	Internet of Things
KPI	Key Performance Indicators
RH	Relative Humidity
IR	Infrared Radiation
USB	Universal Serial Bus
MQ	Metal Oxide Semiconductor
PPM	Parts Per Million
OLED	Organic Light-Emitting Diode
I2C	Inter-Integrated Circuit
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver/Transmitter
ADC	Analog-to-Digital Converter
ARM	Advanced RISC (Reduced Instruction Set Computing) Machine
GND	Ground
VCC	Voltage Common Collector
SCI	Serial Communication Interface
SDA	Serial Data Line
PCB	Printed Circuit Board
MQTT	Message Queuing Telemetry Transport