Towards the Development of an Affordable, Miniaturized, Low Power Consumption Liquefied Petroleum Gas Leakage Detector for Environmental Safety

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Abstract
There is limited availability and usage of cooking gas leakage detectors for fire safety purposes in developing countries of Africa owing to their high cost, unstable electric power supply source and inefficient gas sensor architecture although over 80% of the population relies on liquefied petroleum gas (LPG) for cooking. Unfortunately, LPG cookers are associated with most fire and gas explosions in this region because of its high flammability emanating from gas leakages within the system, leading to environmental hazards. This paper presents the development of low cost, reduced electric power consumption, miniaturized LPG gas leakage detector. The developed device implements unique system for the detection of LPG gas, triggers an alarm through a buzzer upon detection of leakage, and delivers a warning short message service (SMS) to the enrolled users prompting them of the LPG gas leakage or incomplete combustion of the LPG gas at the burners. The deployed circuitry demonstrates high levels of efficiency, reliability, and is affordable, therefore is attractive for low-income countries of Africa.

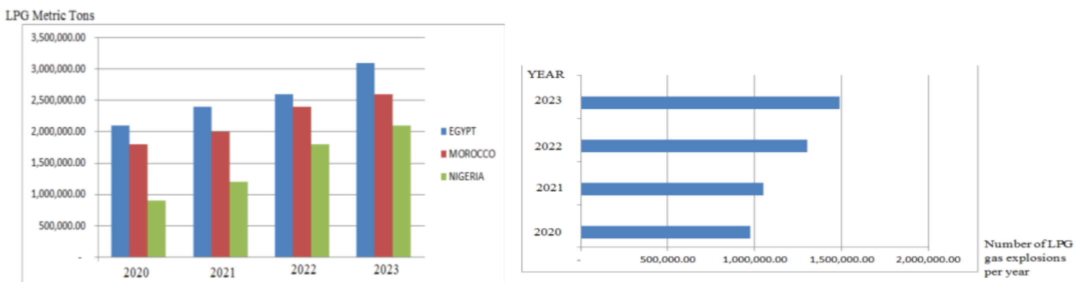
***Keywords**:* Environmental hazard; fire safety; gas leakage detector; gas sensor; gas explosion

1.0. Introduction

The rapid increase in the rate of reported gas explosions in Africa correlates with the rise in population of people using cooking gas according to Xinming *et al*. (2023). Studies have shown that these explosions have been attributed to leakages from cooking gas either from the burners or from the LPG cylinder regulators. Although, the accidents associated with the explosions caused by cooking gas can be curtailed using LPG detector systems, they are rarely deployed in Africa because of high cost making them unattractive.

There is a dire need for LPG detector device in all homes in Africa to curtail the menace of explosions due to leaking LPG. The accidents emanating from leaking LPG is usually catastrophic, leading to a chain reaction of fire that destroys numerous buildings in a flash. Most low-income countries of Africa are filled with sites of poorly planned community buildings crowded together making them susceptible to the spread of fire. As these communities continue to adopt the use of LPG for cooking, it exposes them to more dangers of explosions from the LPG as reported by Kholmanov and Shamsuddinova, (2024).

The rate of Liquefied Petroleum Gas (LPG) consumption in African countries varies significantly from one country to another due to factors such as population size, infrastructure development, government policies, and cultural practices such as deforestation as reported by Sabrina *et al.*, (2017); Sapnken *et al.*, (2023). However, inadequate and often unstable power supply from the national grid, and the rising cost of kerosene coupled with issues of kerosene adulteration in African countries, have pushed up the demand for the consumption of LPG in the continent. Yearly, this rate keeps increasing swiftly owing to its perception of being clean, cheaper and readily available as a reliable source of energy for domestic home usage, industrial heating, and heat generation purposes when compared with other conventional sources of energy such as firewood. In addition, it is currently being adopted as an alternative fuel for automobiles Sarah (2022). The increasing usage of LPG in three African countries is presented in Figure 1(a). The corresponding increase in the number of LPG explosions in Africa is as shown in Figure 1(b).



1(a) 1(b)

Figure 1: (a) Increase in the rate of the use of Liquefied Petroleum Gas across three African Countries – Egypt, Morocco, and Nigeria. 1(b) Number of LPG gas explosions in Africa.

The multiple bar chart in Figure 1A shows that Egypt recorded the highest rate of LPG consumption from the year 2020 to 2023. This increase in LPG consumption amongst the African countries corresponds with the increase in rate of accidents often leading to death, fire, destruction of buildings and properties, and suffocation, linked to gas leakage and explosion of gas cylinders as stated by Rasbash (1980), and Xinming *et al*., (2021). Previous reports by Okonkwo *et al.* (2020) have shown that the major causes of these accidents are faulty cylinders, faulty valves, and worn-out regulators, illegal or over filling of gas cylinders and lack of technical know-how on the part of the users of gas cylinders.

Liquefied Petroleum Gas (LPG) is a highly flammable gas, and if a leak occurs, it can lead to a fire or explosion with potentially devastating consequences as noted by Mathias (2016), and Parate *et al*., (2024). Thus, the need for a technology that can provide early warning alert for any leakage of gas if present up to a certain level of concentrations in parts per million in any environment, to ensure that users have enough time to avoid danger, the destruction of lives and properties.

The LPG sensor with Global System for Mobile Communications (GSM) module is a useful application for detecting and alerting users of potential LPG gas leaks. Over the past decade, the development of LPG sensors has seen significant advancements in technology, performance, and applications driven by the increasing demand for safety, efficiency, and environmental responsibility in various industries and applications as stated by Ashish *et al*., (2021) and Green and Chang, (2004).

The earlier models of LPG sensors (catalytic models, Bhaduri *et al*. (2021), semiconductor models, More *et al*. (2008), and infrared models, Kasai *et al*. (2011)) from 2010 to 2023 primarily focused on industrial and commercial applications, such as gas leak detection in factories, warehouses, and processing plants. Sensor technologies in this era are based on various principles, including catalytic, semiconductor, and infrared absorption, each with its own advantages and limitations as reported by Hee-Tae (2022).

The limitations of the existing gas detectors in African countries can stem from a variety of factors, including technical, economic, and infrastructural considerations. Some common limitations are low sensitivity and slow response times; poor selectivity for LPG detection, detection of false alarms which endangers safety; poor analysis of gas mixtures and bulkiness of device; high power consumption and limiting battery life in portable applications. Most of these gas detectors which mainly are imported need to be regularly calibrated and maintained to ensure accurate and reliable performance. However, in some African countries, access to calibration gases, spare parts, and certified technicians may be limited, leading to issues with the reliability of the equipment.

To address these limitations, it is important to consider the specific needs and capabilities of African countries when selecting gas detection technologies according to Juntao *et al*. (2011), and Anyaoha *et al*. (2020). This may involve developing or adapting solutions that are better suited to local conditions and exploring funding mechanisms to make these technologies more accessible. The approach of this paper is to leverage on the advancements in gas sensing and communication technologies to create efficient and cost-effective solution for LPG leak detection and alerting. The developed system targets to improve safety and minimize the waste of LPG by promptly detecting leakages.

2.0 Materials and Methods

2.1 Operational Principle

The block diagram describing the operation of the developed LPG detector system is presented in Figure 2.

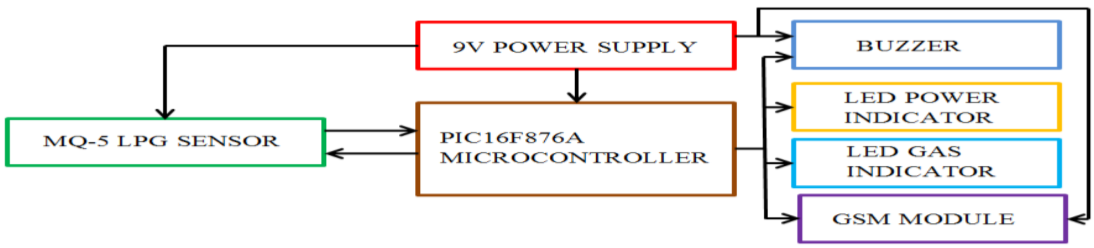


Figure 2: Block diagram of the developed LPG leakage detector

The operation of the developed LPG detector device is as shown in the flowchart in Figure 3. The operation of this LPG gas sensor is based on the principles of gas detection by ionization of the target gas molecules by a semiconductor material as stated by Fang *et al*., (2002). The sensor utilizes the interaction between LPG molecules and a semiconductor material to detect the presence of the gas. When LPG comes in contact with the surface of the semiconductor component of the MQ-5, it causes a change in the electrical properties of the semiconductor material. This change is often related to the absorption of LPG molecules onto the surface of the semiconductor, which alters its conductivity. The MQ-5 sensor typically consist of a sensing element made of a semiconductor material such as tin dioxide (SnO_2) or zinc oxide (ZnO), and a set of electrodes for measuring the electrical response as previously reported by Gassman and Chaudhry (2012), Murvaya (2011), and Compton (2014).

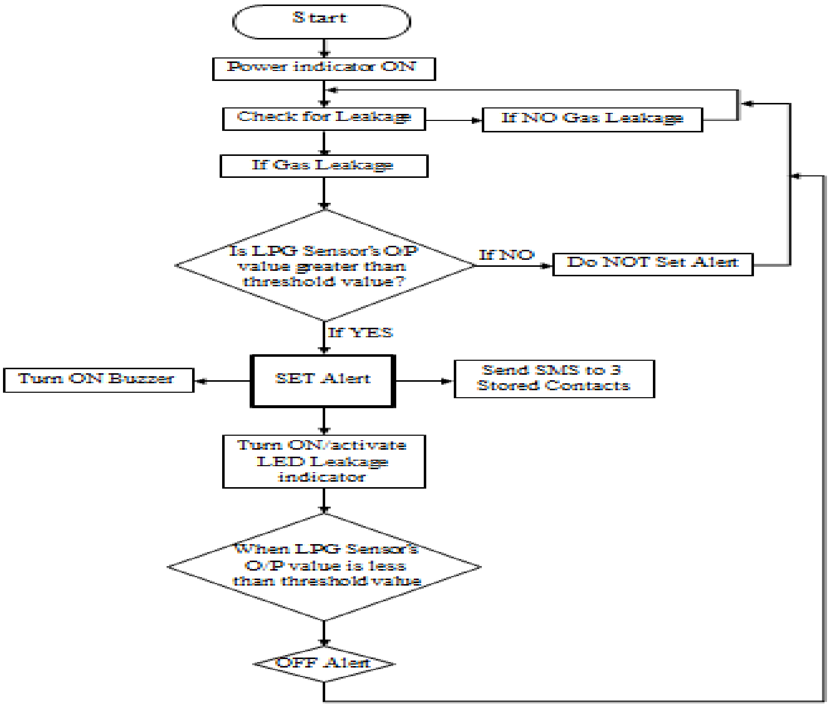


Figure 3: Flowchart of the LPG detector device

When the LPG comes in contact with the sensing element, it causes a change in the resistance of the semiconductor, which is measured as a change in voltage or current. This change in resistance is the basis for detecting the presence of LPG. The interaction between LPG and the semiconductor surface is influenced by various factors, such as the concentration of LPG, temperature, the chemical composition of the semiconductor material, the sensitivity and selectivity of the sensor to LPG gas. The device sensitivity determines its ability to detect low concentrations of LPG, while selectivity pertains to its ability to distinguish LPG from other gases that may be present in the environment as stated by Folga (2007), Ameer *et al*., (2015), and Baratto *et al*., (2011).

Hence, when the device is placed in an area where LPG is in use, for instance in the kitchen or near gas appliances, the sensor continuously monitors the level of LPG gas within the location. If the sensor detects a high concentration of LPG, it triggers the oscillator of the PIC16F876A micro-controller, which then activates the GSM module. The GSM module uses the SIM card to send a predefined message to the user's mobile phone, alerting them about the gas leak. First the sensor will sense the leakage on the basis of gas density which is then sent to the PIC16F876A microcontroller in the form of electrical signal and further through programming/coding fed in the PIC16F876A microcontroller, a signal will be sent to the peripheral components and the buzzer will be activated.

The green light emitting diode (LED) comes ON once the power switch is activated indicating that the system is connected to electric power from the 9 Volts power source. If the green LED fails to light, it shows that the device is faulty. Either the battery is dead or there is an open circuit in the device. It therefore indicates when the device malfunctions to alert the user to quickly get the fault fixed.

The red LED switches ON immediately the device senses the LPG within the area. The sensitivity is based on the set concentration of the LPG programmed in the microcontroller. The level of LPG within the target area may increase due to a leakage of LPG from the burner of a cooking gas or from the hose or from the gas cylinder regulator. As the red LED switches ON indicating the detection of LPG, simultaneously the buzzer generates the alarm and SMS message is also delivered to the two enrolled GSM numbers. The auto recorded SMS alert reads, "LPG leakage detected!" The basic components of the developed LPG detector device are as shown in the block diagram Figure 2.

The circuit diagram of the LPG detector device is presented in Figure 4.

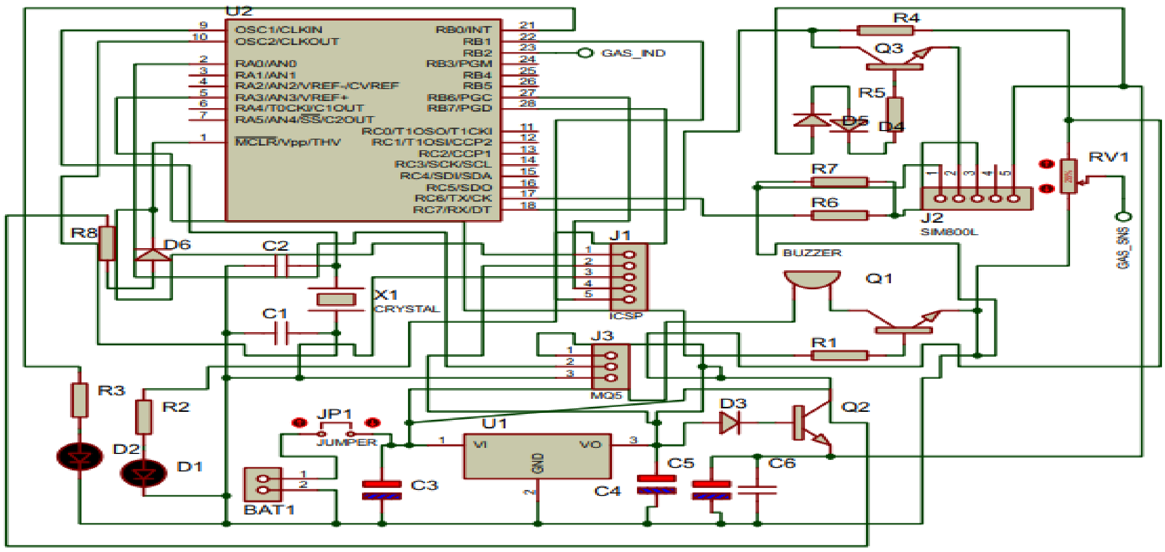


Figure 4: Circuit diagram of the LPG detector device

The simulation software employed for testing the validity and performance of this device circuit design is the Proteus ISIS and ARES simulators. These tools are widely used in the fields of electronics and electrical engineering for simulating and designing electronic circuits, offering a comprehensive set of features for designing, simulating, and creating printed circuit boards according to Sushmitha and Sunithaa, (2012), Didpaye1and Nanda, (2015), and Anon (2007). The Printed Circuit Board (PCB) was designed using the Proteus-ARES. The Proteus-ARES is the PCB layout module within the Proteus software suite. The PCB layout is presented in Figure 5(a). The transfer process of the PCB to a bottom copper plate using electric pressing iron is shown in Figure 5(b).

Figure 5(a): The PCB Layout

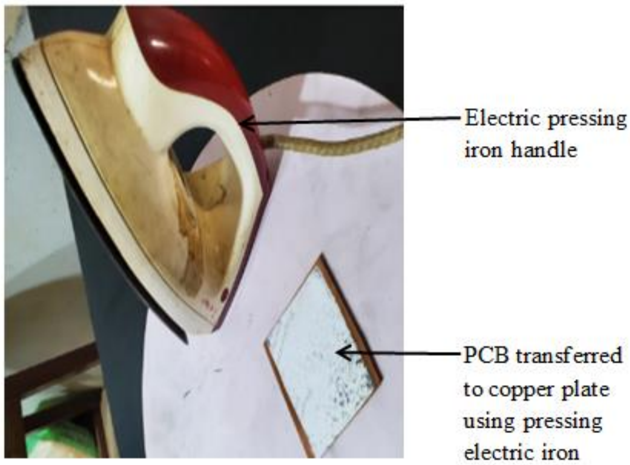


Figure 5(b): The transfer of the circuit layout to a copper plate creating the PCB layout

Implementing a printed circuit board miniaturized the size of the developed LPG detector device enabling it to be positioned close to the possible source of any LPG leakages and reducing the electric power consumption of the device. The packaging of the developed device is as shown in Figure 6. The side view of the packaged device reveals the electric power ON and OFF switch from where it is activated. Once the switch is ON, the green LED turns ON. The top view shows the red LED, green LED, the buzzer, and the battery. The red LED turns ON immediately LPG is detected. The alarm sounds through the buzzer alerting the users of LPG leakage. A 9 volts battery powers the developed device. An insulated metal box is used in the packaging of the device to protect it from fire.

The metal casing protects the device from physical impacts that may damage the device making it very rugged. Also, the metal casing protects the device from moisture and other environmental conditions that can cause the degradation of the PCB and the electronic components. The cost of the developed LPG detector device is presented in Table 1. The electronic components where all purchased in Lagos, Nigeria at their unit prices. During mass production of the developed device, the cost will be greatly reduced due to bulk purchases.

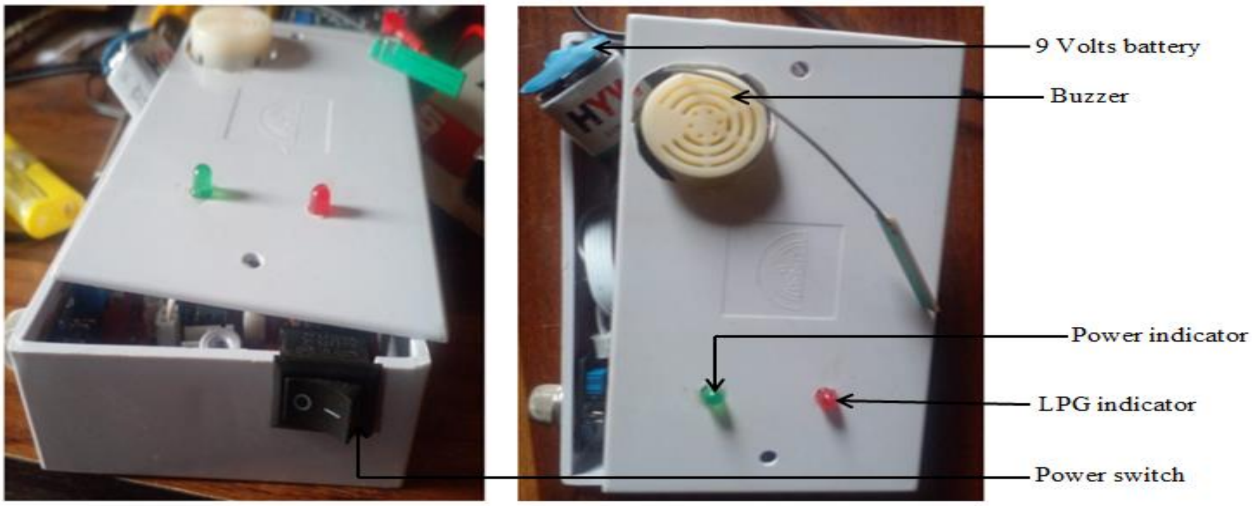


Figure 6: The side and top view of the developed LPG detector device

Table 1: Components of the LPG detector and their unit costs

S/N	Components	Quantity	Amount (N)
1.	22pF Ceramic Capacitor, 100nF Ceramic Capacitor	2pcs, 1pc respectively	40.00
2.	1000uF/25V Electrolytic Capacitor, 100uF/16V Electrolytic Capacitor	1pc, 2pcs respectively	100.00
3.	1k ohms resistor, 4.7k ohms resistor, 5.6k ohms resistor	2pcs, 1pc, 1pc respectively	20.00
4.	330 ohms resistor, 10k ohms resistor	2pcs each	30.00
5.	7805 - 5V voltage regulator	1pc	1,000.00
6.	PIC16F876A - Microcontroller and MQ-5 LPG Gas Sensor	1pc each	8,000.00
7.	6x3 convertible box with Cover and 2PIN Terminal block	1pc each	1,100.00
8.	BC547 Transistor, TIP41C Transistor	2pcs, 1pc respectively	900.00
9.	1N4007 Rectifying Diode, 1N4148 Signal Diode	3pcs, 1pc respectively	400.00
10.	9V Battery and 28pins IC Sit	1pc each	1,200.00
11.	12V Buzzer and SIM800L SIM Module	1pc each	750.00
12.	PCB Copper Plate (Vero board)	1pc	500.00
13.	4MHz Crystal Oscillatory Capacitor	1pc	250.00
14.	Jumper Wires, Jumper Pins and Jumper Keys	5pcs, 10pcs and 10pcs resp.	450.00
15.	LEDs	2pcs	100.00
16.	Bus Wires (twin red/black)	1m of 1.5mm	100.00
	Total		14,940.00

3.0. Results and Discussion

3.1. Testing and validation of the developed LPG detector

The developed LPG detector was mounted on the ceiling at different distances away from the gas cooker in an evacuated building. A fire extinguisher was positioned at the location of the test which had only the cooking gas in the kitchen with the gas cylinder supply placed outside at the corridor. All safety and personal protection equipment were in place. The response time of the device was recorded as the distance away was increased from 2 meters to 3 meters in space of 1 meter. At each trial, the gas cooker knob was turned ON for 10 seconds and then turned OFF allowing the discharge of LPG. The time the alarm sounds and the time the SMS alert was delivered was recorded. The time between the LPG detection time and the alarm OFF is also recorded as the recovery time.

3.2. The performance of the LPG detector device

Ten trial tests were conducted at different distances away from the gas cooker. The obtained result is presented in Table 2.

Table 2: Validation of the developed LPG detector device

Trials	Distance from gas cooker (in meters)	LPG detection time (in seconds)	Time SMS delivered (in minutes)	Recovery time (in minutes)
1st	2	10	2	1
2nd	3	15	6	2
3rd	4	22	10	2
4th	5	35	30	3
5th	6	106	25	2
6th	7	120	28	3
7th	8	125	55	3
8th	9	139	67	4
9th	10	190	70	4
10th	11	250	81	3

The developed LPG detector performed well, triggering alarm and delivering SMS message each time the gas cooker was turned ON. The 5th to 10th trials gas detection time increased because the dimension of the kitchen could not contain the distance. So, the doors were left open and the distance extended to the nearby rooms. The recovery time was within 5 minutes. The SMS delivery time was within 2 hours. The SMS delivery time is dependent on the stability of the telecommunication network. Sometimes the network can fail and there will not be any message delivered.

3.3. The strength of the developed LPG detector device

The strength of the developed LPG detector is in its low cost, ruggedness, efficiency and serviceability. The cost of producing the prototype is N14,940.00 (Fourteen thousand nine-hundred and forty Naira) which is comparatively low considering the cost of the available variants in the market currently at N50,000.00 (Fifty thousand Naira) plus. The packaging of the device in a metal box makes it very rugged and durable. Most of the available variants in the market are packaged with plastics. The demonstrated efficiency of the developed LPG detector as shown in the test trial results in Table 2 validates its high efficiency and reliability. All the components used in the construction of the device were locally sourced in Nigeria. Any faulty component can easily be replaced so the developed device is very serviceable.

3.4 Limitations of the developed LPG detector device

This work focuses on the detection of LPG leakages for homes that uses the gas cooker. It does not cover the analysis of LPG contaminants or its application in industrial scales. The developed device may not send an SMS message to the user(s) when there is a drop in the input voltage supply. To overcome this, there is need to maintain a constant input voltage supply of 9V from the battery or incorporate the device with an adapter of 12V input voltage and an output of 9V. This will help to maintain the 9V input voltage needed to operate the system and to alert the user(s) with an SMS message. The programming of the arduino microcontroller is not included in this paper however the code will be made available on request by the corresponding author.

4.0. Conclusion

The limitations of the existing LPG detector devices that make them unattractive for Africa have been identified and discussed in this paper. This paper proposed a cost effective, reliable and efficient LPG detector device that is suited for Sub-Saharan Africa. The developed prototype is mass producible, serviceable, and easy to install. The quoted cost of development of the prototype will be reduced further during commercialization owing to bulk sourcing of the components. The long-term impact of this developed device will translate to the elimination of accidents associated with LPG leakages.

Data availability

All data generated are included in the paper. The microcontroller code will be made available by the corresponding author upon request via email.

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