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Research article

Real-time H_2S detection kit for hydrogen fuel cell

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A R T I C L E I N F O

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Proton exchange membrane fuel cells (PEMFC)
Internet of things (IoT)
Sensor
Printed circuit board (PCB)
Wireless communication

A B S T R A C T

Among hydrogen technologies, a proton exchange membrane fuel cell (PEMFC) is known as an efficient device using hydrogen as the fuel. Although different real-time fault-diagnosis methods are available (i.e., voltage-based or electrochemical-based), the problem with these methods is their dependency on being directly connected to a computer, higher costs, lower security, and the need to perform the tests in a laboratory. The focus and the solution of this study are to propose a novel design of printed circuit board (PCB) that enables the implementation of the required sensors to detect/measure the operational parameters/contamination of PEMFC. The communication of the considered PCB will be with a server without direct contact through the Internet of Things (IoT). A specified computer. exe file has also been developed to directly connect to a personalized network hotspot (to increase security) and enable the wireless communication of the sensor and the computer. The outputs of this study can be considered a novel fault diagnosis kit that measures H_2S wirelessly using IoT. To verify the result 11 ppm and 12 ppm of H_2S was injected into the system, the IoT kit's measured data is compared with the experiments. The results comparison validated the suitability of the system.

1. Introduction

With the current limitations for the usage of fossil fuels, hydrogen has been suggested as an alternative [1–3]. Using hydrogen as the fuel, proton exchange membrane fuel cell (PEMFC) can produce electricity with water as the side product without any other emission [4–7]. PEMFCs can be used both in low and high temperature conditions in which the former is mainly suitable for portable applications such as hydrogen cars, and the latter is for stationary usages [8]. Considering the recent initiatives to reach net-zero carbon and pollutant-free industries, the transition from combustion engines to fuel cells and batteries is needed with special considerations on the heat transfer [9–13].

Although PEMFCs are efficient considering the output power and the environmental aspect compared to fossil fuel-based power generators, the lifetime should be considered deliberately [14]. Although there have been many studies on the durability of the PEMFC systems [15] and operational parameters optimizations [16], further attention should be given to the real-time detection of H_2S contamination in PEMFC just like similar studies that have tried to mitigate the hydrogen sulfide amount in different applications [17]. Based on the defined targets by the Department of Energy (DOE), the lifetime of 8000 h at a voltage of 0.8 V and the performance of

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300 (mW/cm^{-2}) is aimed at 2025 [18].

The recent advancements in autonomous sensing systems have led to novel designs of printed circuit boards (PCBs) that enable wireless communication through the Internet of Things (IoT) [19]. The more efficient design of the PCBs enables the low-cost, energy-efficient, more compact, multi-purpose processing/sensing in different domains [20]. For example, all the existing environmental/operating parameters can be controlled/measured in the domains of home automation, mobile health care, medical aids, smart grids, automotive, traffic management, industrial automation, food contamination, etc. [21].

The development of smart sensors has enabled the advancement of intelligent systems that can monitor/control industrial processes. The conventional methods were to measure the changes of a parameter (e.g., temperature, degradation, contamination, etc.) using a sensor followed by manual post-processing of the measured data by a human operator [22]. However, the post-processing (including calibration and the impacts of aging/temperature, etc.) and telecommunication can be done by IoT in a dedicated software [23]. In other words, IoT enables the communications of computer systems and sensors without the involvement of human operators [24]. Recent studies have also demonstrated the role of machine learning and deep learning in facilitating automated fault diagnosis of pipelines [25] and to monitor spatially distributed cracks using distributed fiber optic sensors [26], respectively. Wireless machine-to-machine communication also minimizes human errors, increases safety (e.g., sensing the contaminants that can have adverse effects on health), enables complex measurements (e.g., sensing and communication when human access to the sensor is not possible), and reduces the operational costs [27].

Recent investigations have suggested the integration of smart sensors and IoT in different sectors [28]. Tariq et al. [29] developed real-time measurements of the temperature, humidity, pressure, geo-position, Nitrogen dioxide, etc. as air pollution parameters to optimize the air quality at Qatar University. The results indicated that the developed methodology can optimize the desired output independently from the commutative anomalies. Sharma et al. [30] used a similar concept to detect fire locations in agricultural domains using fuzzy logic. The implementation of IoT in that project enabled reporting of the active fire locations to the stakeholders and government agencies to prevent the fire spread in addition to the determination of the farmers' names involved in the burning. Although the integration of IoT and sensing devices can be found in a wide range of usages, the proposed methodology has not been implemented in the field of fuel cells yet.

Among different types of methods to improve the durability of the PEMFCs, preventing the cell from contamination and establishing the methodology to measure and communicate the contamination level is the goal of this study. Although using the sensors is more reasonable to detect the contamination, compared to voltage/electrochemistry-based methods, communication of the data, security, calibration, costs, and dependency on being connected to a computer are the limitations that should be solved. The goal of this study is to propose a kit that uses a novel PCB, where the sensor will be located, and is connected to a Wireless Fidelity (Wi-Fi) module to transfer the measured data to a Personal Computer (PC). To ensure security, the kit will only work with a specified domain of the network (e.g., personal hotspot of a cellphone). For the calibration and the post-processing of the results, computer software has been developed that directly presents the measured data by the sensor in a real-time condition in the same domain of the network (e.g., personal hotspot of a cellphone). Calibration of the data can be also done using the developed computer software. Considering the costs, the kit is considerably cheaper than voltage-based and electrochemistry-based fault-diagnosis methods. The kit is also cheaper than the available sensors in the market (that are not using IoT, they are connected to a PC directly in a wired manner, there is no specified computer software assigned to the measured data, requires the presence of a person on-site, calibration should be done physically, etc.)

Embodiments of the present invention are related to the PCB layout of the fuel cell monitor system, which should be assessed through the network (or internet). More particularly, embodiments related to the positioning, selection, and design of the most important sensors which can monitor the fuel cell performance and degradation, software that retrieves information from the sensed values, and methods that are utilized to provide access through the network (or internet) on a single PCB board. The layout of the PCB includes several design considerations such as size, weight, energy consumption, and shape to ensure the comfortable operation of the control system by a user.

In one embodiment, the proposed kit provides a set of sensors (current, voltage, humidity, and temperature, and Hydrogen Sulfide) that measure the performance, degradation, and contamination of the PEMFC. The reason for selecting Hydrogen Sulfide was to include a detecting procedure of a contaminant in a PEMFC. The current, voltage, humidity, and temperature sensors were selected as the representative of the operational parameters of the PEMFC.

In another embodiment, the proposed kit provides software that runs in the provided microcontroller and retrieves the information from the sensed values. This information is then passed to the trans receiver modules to transfer to the users through the wired,e.g., Recommended Standard (RS)-232, RS-485, Universal Serial Bus (USB), or On-Board Diagnostics (OBD) II, or wireless,e.g., Global System for Mobile communications (GSM) or WiFi, links. It should be noted that the method of transfer depends on the preference of the user and any type of data transferring method can be used. Furthermore, the commands that are generated from the users will be passed to the microcontroller for processing through the communication modules.

In another embodiment, the communication modules provide different interfaces to connect the monitor system to external systems where the produced information is sent. The communication modules are selected so that the monitor system can be easily connected to a wide range of external devices by supporting various protocols and standards.

2. Detailed description and experimental methodology

The architecture of the PCB depicted in Fig. 1 (further details about Fig. 1 are presented in the Appendix) has three groups of components, i.e., sensing components, processing components, and communication components. With the aid of this PCB alongside fuel cells, the performance of these cells can be monitored and utilized more efficiently. Fig. 1 also shows the schematic of the PCB and its elements, i.e., the current sensor, voltage sensor, humidity and temperature sensor, Hydrogen Sulfide sensor, Microcontroller, Wireless transmitter/receiver module, Wired transmitter/receiver module, and vehicle interface. Table 1 also describes the components used in Fig. 1. It should be noted that including all the details of the designed PCB in one figure demanded decreasing the font of the contents in Fig. 1, hence, the details of this figure are enhanced in separate figures that are shown in Appendix starting from Fig. 1(s) to Fig. 12(s).

As mentioned, the architecture of the proposed monitor system has three groups of components, i.e., sensing components, processing components, and communication components (see Fig. 1). The processing components of the proposed monitor system will be introduced in detail. The main part of the processing element in the proposed monitor system is the ESP32 microcontroller from Espressif company. ESP32 has two 240 MHz processing cores and supports many communication protocols such as Wi-Fi and Bluetooth which simplifies development processes. Furthermore, it includes many peripheral circuits required to connect the mentioned sensors. The ESP32 is also responsible for running the main program which is developed to handle the monitor system operations.

Fig. 2 shows the two-dimensional view of the proposed monitor system. Due to the high current range of the fuel cells, the shunt is used to measure the electric current from the fuel cell with high precision by the current sensor utilized in the monitor system. To measure the current value, the voltage across the shunt resistance, which is a low resistance, is converted into current by the equation V=RI. A 12-bit Analog-to-Digital (AD) converter is used to measure the voltage of the two ends of the shunt resistance by the internal AD converter in the microcontroller. Then, the current information is sent to the controller and used to optimize the currents and accurately control the performance of the fuel cell. The use of internal AD converters of the microcontroller can reduce the complexity of the circuit compared with utilizing external AD converters, and it also consumes less power.

The proposed monitor system also utilizes a voltage sensor as can be seen in Fig. 2. The output voltage of the fuel cell is measured by this sensor. The sensed value helps the monitor system optimize the output voltage by changing the input of the fuel cell and applying appropriate configuration according to the application's requirements. Like the current sensor, the voltage sensor utilizes the 12-bit internal AD converter of the microcontroller.

The proposed monitor system also benefits from humidity and temperature sensors. The temperature and humidity of the environment can have a significant effect on the efficiency of the fuel cell. The operating temperature for the membrane inside the PEMFC

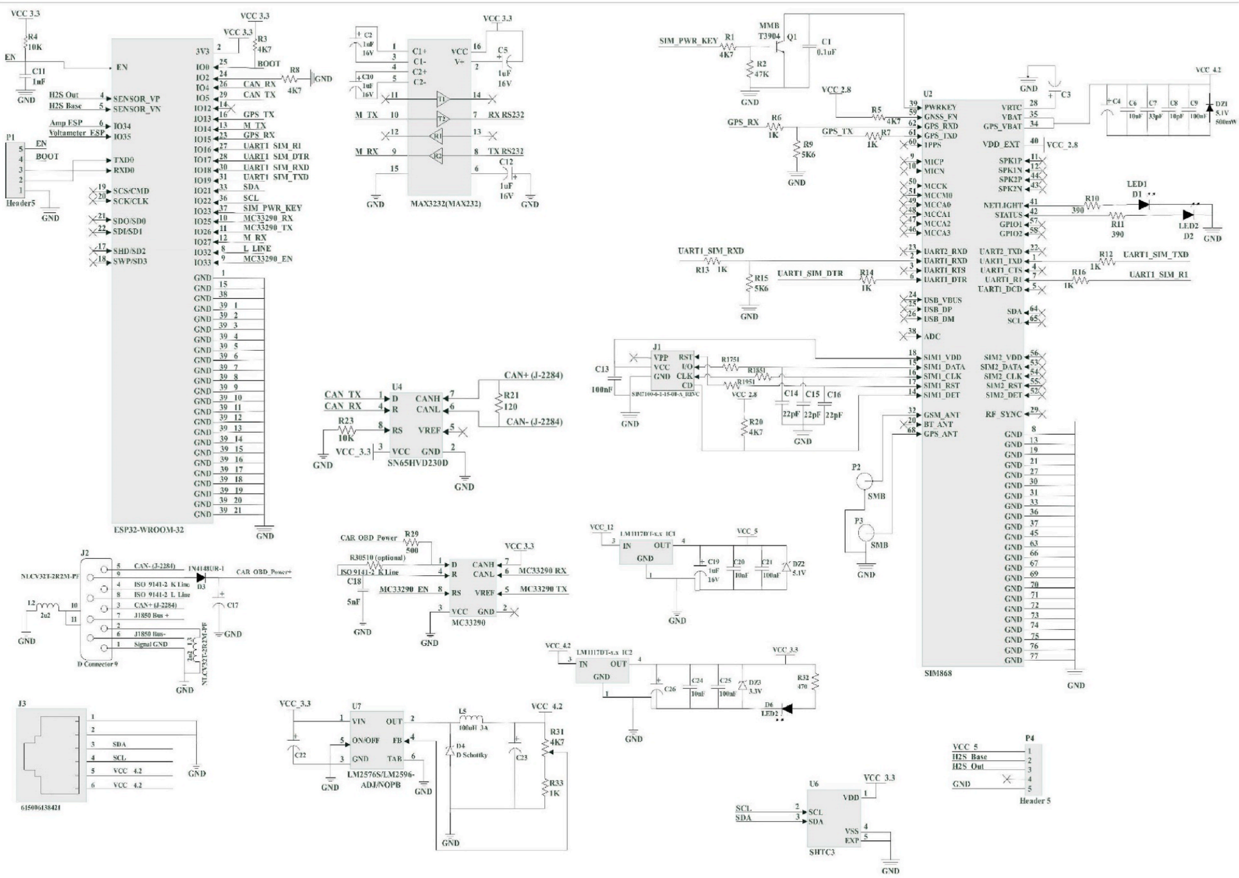


Fig. 1. The architecture of the used PCB in this study.

Table 1
The description of the used components in the proposed architecture.

Designator	Description	Footprint	LibRef	Comment	Quantity
C1	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	0.1uF	1
C2	Cap electrolitic radial	Cap electrolitic radial 5x11-2	Cap ELECTROLITIC TOTAL SIZE	100μF50V	1
C3	Solid Tantalum Chip Capacitor, T510 Series - Ultra-Low ESR	E	T510E		1
C4	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	10uF	1
C5	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	33 pF	1
C6	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	10 pF	1
C7, C9, C18	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	100 nF	3
C8	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	1 nF	1
C10, C11, C12	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	22 pF	3
C13	Cap electrolitic radial	Cap electrolitic radial 5x11-2	Cap ELECTROLITIC TOTAL SIZE	10 nF	1
C14	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	5 nF	1
C15, C16, C19	Cap electrolitic radial	Cap electrolitic radial 10x20-5	Cap electrolitic radial 10x21	Cap 10x21	3
C17	CAP 0805	CAPC3413 × 12 N	CAP SMD 0805	10 nF	1
D1, D2, D6	Typical RED, GREEN, YELLOW, AMBER GaAs LED	3.2X1.6X1.1	LED2	LED2	3
D3, D5	DIODE GEN PURP 75V 200 MA DO213AA	SOD80, LL-34	1N4148UR-1	1N4148UR-1	2
D4	Schottky Diode	SMB	D Schottky	D Schottky	1
DZ1	DIODE ZENER GENERAL	SOD80, LL-34	ZENER GENERAL DIODE	5.1V 500 mW	1
DZ2	DIODE ZENER GENERAL	SOD80, LL-34	ZENER GENERAL DIODE	3.3V	1
E1, E2	Generic Antenna	PIN1	Antenna	Antenna	2
IC1	x.x Volt, 800 mA Low-Dropout Linear Regulator, 3-pin TO-252	TD03B_N	LM1117DT-x.x	LM1117DT-x.x	1
J1	DC-DC Converter Output Input	PJ-313	PJ-313	PJ-313	1
J2	7 _6 + 1_ Position Card Connector Micro SIM Surface Mount, Right Angle Gold	GCT_SIM7100-6-1-15-00-A_REVC	SIM7100-6-1-15-00-A_REVC	SIM7100-6-1-15-00-A_REVC	1
J3	Receptacle Assembly, 9 Position, Right Angle	DSUB1.385–2H9	D Connector 9	D Connector 9	1
J4	Jack Modular Connector 6p6c (RJ11, RJ12, RJ14, RJ25) 90Â° Angle (Right) Unshielded Cat5	615006138421	615006138421	615006138421	1
L1, L2	2.2 μH Unshielded Wirewound Inductor 770 mA 169 mOhm Max 1210 (3225 Metric)	INDM3225 × 240 N	Inductor 2.2 μH 770 mA 1210	NLCV32T-2R2M-PF	2
L3	POWER INDUCTOR 10x12 (200 mils)	Inductor 10x12 (200 mils)	POWER INDUCTOR 10x12 (200 mils)	100uH 3A	1
P1	Header, 5-Pin	HDR1X5	Header 5	Header 5	1
P2, P3	SMB Straight Connector	SMB_V-RJ45	SMB	SMB	2
P4	Header, 4-Pin	HDR1X4	Header 4	Header 4	1
P5	Header, 6-Pin	HDR1X6	Header 6	Header 6	1
Q1, Q2, Q3, Q4	NPN Switching Transistor	SOT23_N	MMBT3904	MMBT3904	4
R1, R3, R5, R8, R20	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	4K7	5
R2	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	47K	1
R4, R23, R27, R28, R31, R32	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	10K	6
R6, R7, R12, R13, R14, R16, R35	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	1K	7
R9, R15	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	5K6	2
R10, R11	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	390	2
R17, R18, R19	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	51	3
R21	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	120	1
R22	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	510	1
R24	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	2K2	1
R25	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	500	1
R26	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	510(optional)	1
R29, R30	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	30K	2
R33	Square Trimming Potentiometer	3296W	RES_POT	4K7	1
R34	RES 0805	RESC3413 × 04 N	RES 0805 0.125W	470	1
T1	4 Pitch: 5.08 mm Color: green Contact surface: Tin Assembly	MSTB 2,5/4-G-5,08	CON_Phoenix_MSTB_04	1759033	1
U1	SIM868 GNSS, GSM RF mikroBUSâ„¢ Clickâ„¢ Platform Evaluation Expansion Board	XCVR_SIM868	SIM868	SIM868	1
U2	Bluetooth, WiFi Transceiver Module 2.4 GHz ~ 2.5 GHz Surface Mount	MODULE_ESP32-WROOM-32	ESP32-WROOM-32	ESP32-WROOM-32	1

(*continued on next page*)

Table 1 (*continued*)

Designator	Description	Footprint	LibRef	Comment	Quantity
U3	3.3V CAN Transceiver with Standby Mode, 17 mA, −40 to 85 degC, 8-pin SOIC (D), Green (RoHS & no Sb/Br)	D8_N	SN65HVD230D	SN65HVD230D	1
U4	useing SN65HVD230D instead of MC33290	D8_N	SN65HVD230D	MC33290	1
U5	SIMPLE SWITCHER® 3A Step-Down Voltage Regulator, 5-pin TO-263, Pb-Free	TS5B_N	LM2576S-ADJ/NOPB	LM2576S/LM2596-ADJ/NOPB	1

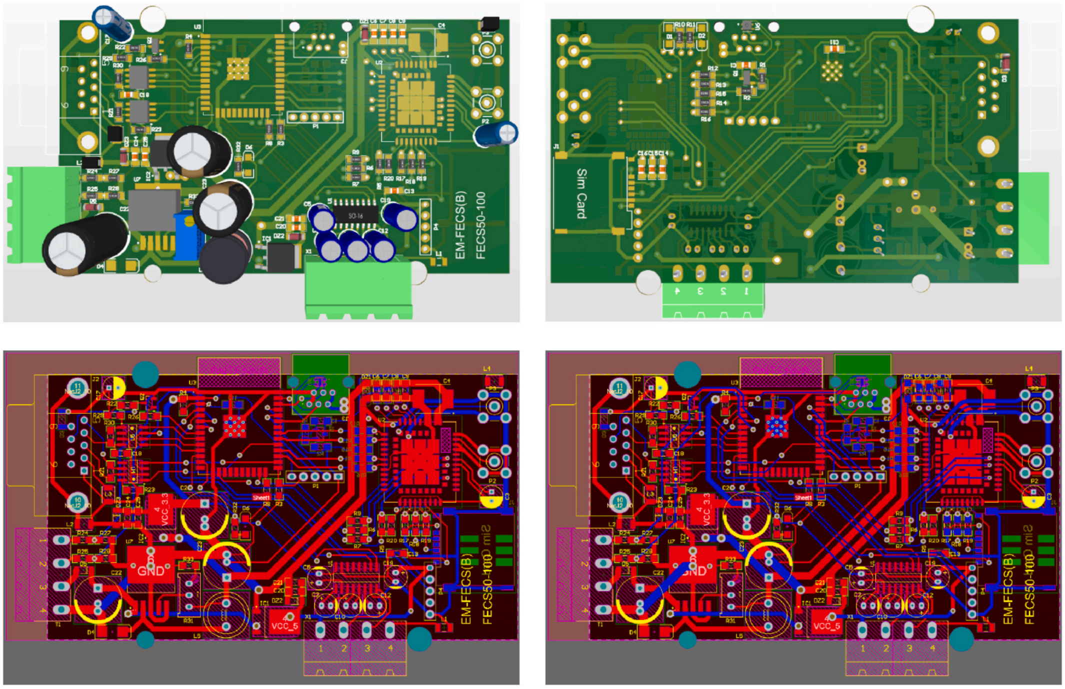


Fig. 2. The two-dimensional view of the proposed monitor system.

stack should be around 65 °C–85 °C to optimize the proton conductivity [31]. Higher temperatures below the mentioned temperature range result in drying of the membrane while lower temperature leads to flooding and extra water inside the cell. A similar concept applies to humidity since the electrochemical operation of the PEMFC is altogether to have saturated water to prevent drying the membrane and increasing the resistivity for proton conductivity. The utilized temperature and humidity sensor measures the values related to the environmental conditions and sends them to the controller to set the appropriate temperature and humidity settings. To this end, the SHTC3 temperature and humidity sensor was used, which has very high accuracy (0.2 degrees of temperature measurement accuracy and 2 % humidity measurement accuracy). It is also considered a very low energy consumption sensor. SHTC3 is connected to the microcontroller with an I2C interface and the clock stretching method was used to save more energy.

The last group of components that were utilized in the proposed monitor system are communication components. The most important module in this group was SIM868 which enables internet connectivity for the proposed monitor system so it can send and receive information to/from the internet. These features allow users to monitor fuel cell status and update settings for lower emissions and higher power by leveraging centralized cloud processing. The protocol used to connect the proposed monitor system to the internet is Message Queuing Telemetry Transport (MQTT), a well-known communication protocol in IoT applications. Furthermore, the SIM868 module can locate the monitor system through an embedded GPS module on it. In this regard, the manufacturing companies of the fuel cell stack can implement this kit on their stacks and provide a maintenance team to predict the performance and the lifetime of each stack in addition to being enabled for taking actions once contamination occurs.

Another communication component utilized in the monitor system is the RS485-RS232 module. RS485-RS232 is a standard communication in industrial environments that is usually used for communication between PLC controllers. Since the first-generation fuel cells are controlled using PLCs, the monitor system is equipped with an RS485-RS232 module to communicate with such fuel cells. The proposed monitor system is also capable of communicating with vehicles through the OBD II interface. Indeed, in a vehicle that benefits from a fuel cell, the proposed monitor system should connect to the vehicle control system through an automotive standard port (OBD II) to obtain information from the fuel cell.

Regarding the verification of the measured H_2S amount, the obtained H_2 S values are going to be compared with the results of the experimental tests. In this case, a certain amount of H_2S contaminant will be injected into the PEMFC system and then the developed kit will measure the existing contaminant separately. If the measured and the injected values are the same, a verification can be concluded.

3. Results and discussion

The other sensor that was utilized in the proposed monitor system is the Hydrogen Sulfide (H_2S) sensor. By detecting and measuring the concentration of H_2S at the input of fuel cells, this sensor provides information to the monitor system that helps to detect failures or the occurrence of fuel cell malfunction. Indeed, during the hydrogen production processes, it is possible to have impurities, hence acting as contaminants for the PEMFC, which uses pure hydrogen as the fuel. The main goal of this study was to prepare a kit that measures the H_2S contaminant at the inlet of the cathode and anode side (it is also possible to have H_2S contaminant on the cathode, where air flows inside the cell). To measure the amount of H_2S in the monitor system, the FECS50-100 sensor which is manufactured by Figaro company was used. It should be noted that the type of sensor is not limited and any other type of H_2S sensor from different manufacturing companies can be used. Additionally, the invention is not limited to the detection of H_2S contaminant, in other words, it is possible to implement other types of the contaminant sensor (e.g., NO_x, SO_x, CO_x, etc.) on the novel PCB, and the proposed monitoring methodology would be the same (i.e., communication of the measured data using IoT and being displayed by the developed software). The output of this sensor was amplified with an EM-FECS amplifier circuit. Then, the output PPM (Part per Million) of hydrogen sulfide is obtained. To have less error in the measurement due to the induced environmental noise and the length of the sensor connection wire, a reference voltage equal to 0 ppm is used. Additionally, Median and Bessel filters were used to remove the noises from the measured real-time data. It is noteworthy to mention that Median and Bessel filters were selected arbitrarily and it is possible to use other types of filters in the back-end of the developed. exe file to report the sensor data. Fig. 3 shows the developed kit to measure the H_2S contamination using the IoT technology.

Fig. 4 shows the developed. exe file that can operate in a computer and connect to the developed kit using the secure network (e.g., a personal hotspot to ensure security). Fig. 4(a) shows the. exe file before operation and the Fig. 4(b) shows the one after the injection of the hydrogen into the system. To test the developed kit, the kit was located in a pipe, that later H_2S was injected. The amount of injected H_2S could be controlled afterward hence the operation of the kit could be tested. At the bottom-left corner of Fig. 4(b), the first raw received data from the sensor are being shown, that includes noises. At the top-right corner of Fig. 4(b) the median filter has been used on the first raw data followed by the Bessel filter that is shown in the top-left corner Fig. 4(b). At the end, the filtered data are rounded to the nearest discrete number in the bottom-right corner of Fig. 4(b). To improve the operation of the filters, the related parameters can be changed through the. exe file, the mentioned numbers in Fig. 4 have been selected arbitrarily to calibrate the system.

Fig. 5 also compares the amounts of the injected H_2S by the operator on the experimental setup with the measured H_2S by the sensor and communicated to the computer using IoT. As can be seen, the obtained data are quite close and the only problem is the oscillation before and after the changes in the values of the injected H_2S. This can be solved by adding more filters or deliberately changing the involved parameters of the existing filters.

Regarding the scientific discussion of the obtained results, the developed kit can measure the amount of injected H_2S contamination with lower costs, high precision, and accuracy, wirelessly, low volume settings, in the remote condition of the server and the sensors, and high speed. Although the existing Electrochemical Impedance Spectroscopy and other available methods are efficient, the pro-

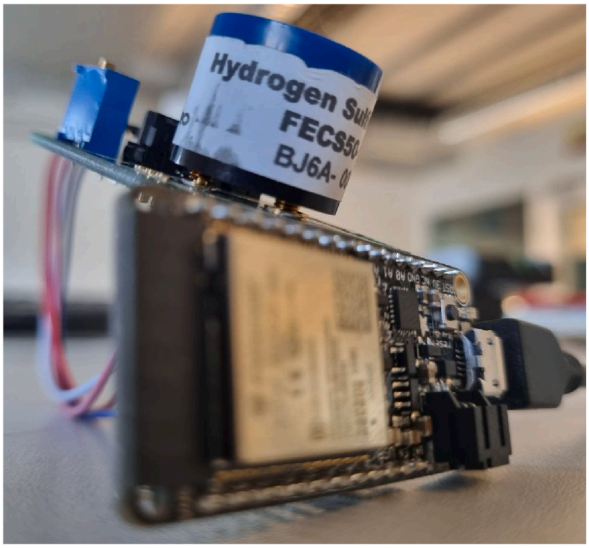
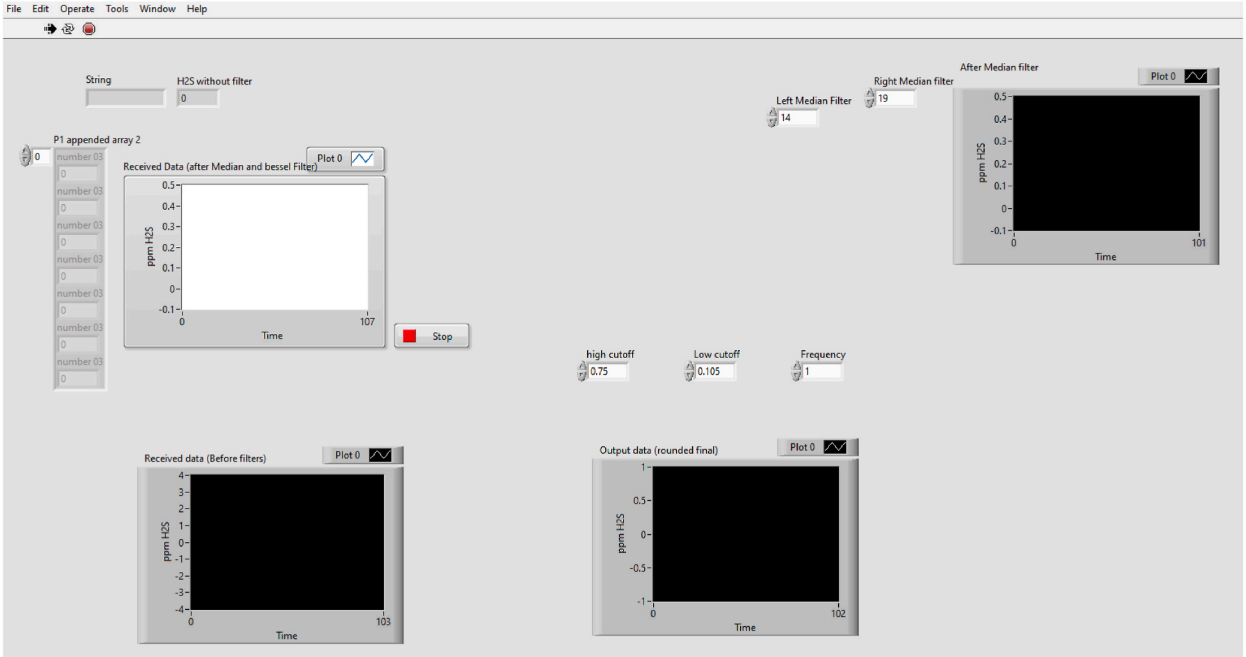


Fig. 3. The developed kit to measure the H_2S contamination using the IoT technology.



(a)

(b)

Fig. 4. The developed. exe file to communicate the obtained data by the sensor to the computer using IoT: (a) the. exe file before operation (injection of the H_2S), (b) the. exe file after operation (injection of the H_2S). It should be noted that the details and the labels in Fig. 4b may not be seen in details due to the lack of camera resolution but they are the same as presented in Fig. 4a. The goal of Fig. 4b is to confirm the operation of the developed H_2 S kit and the changes in the amount of injected contaminant.

posed system can be the next generation of fault diagnosis systems more compactly and efficiently.

4. Conclusion

In summary, this study aimed to pioneer the development of a cutting-edge kit tailored for measuring H_2S contamination in

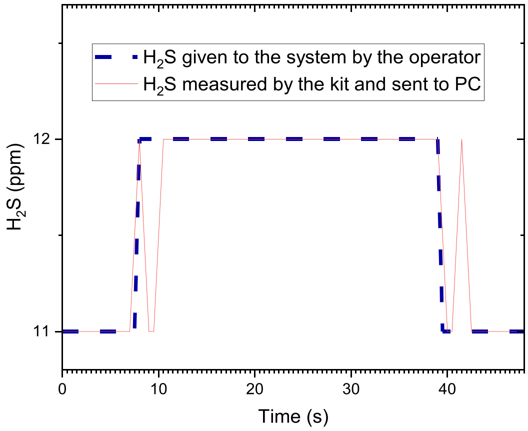


Fig. 5. The amount of detected H_2S by the developed kit and communicated to the system during the experiment compared to the injected value to the test setup.

PEMFCs. The envisioned solution sought to embody qualities of wireless operation, robust security, precise accuracy, compactness, and operational independence, culminating in seamless integration with a dedicated computer. exe file for streamlined data reporting to a server.

Through the meticulous design of a bespoke printed circuit board and the strategic integration of essential sensors, the developed kit successfully achieved the intended objective of measuring H_2S contamination levels. Rigorous experimental validation, involving deliberate injection of H_2S for measurement, underscored the kit's capability for real-time detection with exceptional accuracy, thereby affirming its practical suitability.

Looking ahead, future endeavors could explore the refinement of the kit's capabilities by devising an advanced PCB capable of concurrently measuring all requisite operational parameters. This evolution, coupled with consistent communication methodologies, holds promise for further enhancing the efficacy and versatility of such monitoring systems.

In summary, this article contributes to advancing the state-of-the-art in fault diagnosis methods for PEMFCs, offering insights into innovative engineering design approaches, regulatory compliance, and the broader implications for energy systems with the following key findings:

- Innovation in detection technology

This study introduced a novel H_2S contamination measurement in PEMFCs, emphasizing wireless operation, robust security, precise accuracy, compactness, and operational independence. This innovation aligns with the current trend towards IoT integration and remoted monitoring in engineering systems.

- Practical implementation

By designing a bespoke PCB and integrating essential sensors, the developed kit successfully achieved its objective of measuring H_2S contamination levels. This highlights the practical application of advanced engineering design principles in addressing real-world challenges in energy systems.

- Rigorous experimental validation

This article conducted rigorous experimental validation, including deliberate injection of H_2S for measurement. This validation process in crucial for ensuring the accuracy and reliability of the developed kit, which is essential for compliance with engineering standards and regulations.

- Real-time detection capability

The kit demonstrated real-time detection of H_2S contamination with exceptional accuracy, showcasing its potential for early fault diagnosis and mitigation in PEMFCs. This capability is significant for enhancing the efficiency and reliability of energy systems, thereby contributing to sustainable development goals.

- Future directions

This paper suggests future endeavors could focus on refining the kit's capabilities by devising an advanced PCB capable of concurrently measuring all requisite operational parameters. This indicates a pathway for continuous improvement and innovation in engineering design for energy systems, aligning with the dynamic nature of technological advancements.

CRediT authorship contribution statement

Hossein Pourrahmani: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Ali Javadi:** Writing – original draft, Software, Methodology, Investigation, Data curation. **Amir Mahdi Hosseini Monazzah:** Validation, Supervision, Formal analysis. **Jan Van herle:** Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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