DOI: 10.24427/978-83-68673-38-8_4

Chapter 4. Smart IoT Air Quality Monitoring System

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Streszczenie. Rozdział przedstawia projekt inteligentnego czujnika jakości powietrza opartego na mikrokontrolerze ESP32 i przystępnych cenowo czujnikach środowiskowych do zastosowań wewnętrznych. Opracowano prototyp urządzenia zdolnego do pomiaru temperatury, wilgotności, ciśnienia, stężenia LZO oraz poziomu pyłów zawieszonych. Dane były analizowane i wizualizowane za pomocą platformy ThingSpeak, a system sterowany był z poziomu smartfona. Testy przeprowadzono w warunkach statycznych i dynamicznych, symulujących zmienne środowisko. Wyniki potwierdziły skuteczność, stabilność i wiarygodność działania urządzenia, wskazując jego potencjał w praktycznym monitorowaniu jakości powietrza.

Abstract. The chapter presents a smart air quality monitoring system based on the ESP32 microcontroller and cost-effective environmental sensors designed for indoor applications. A prototype device was developed to measure temperature, humidity, pressure, VOC concentration, and particulate matter levels. The collected data were analyzed and visualized using the ThingSpeak platform, with system control implemented via a smartphone. Tests were conducted under both static and dynamic conditions simulating variable environmental factors. The results confirmed the effectiveness, stability, and reliability of the device, demonstrating its potential for practical air quality monitoring applications.

Słowa kluczowe: jakość powietrza, automatyka budynkowa, czujniki, ESP32, mikrokontrolery

Keywords: air quality, building automation, sensors, ESP32, microcontrollers

Introduction

In today's world, dynamic technological development creates both new challenges and opportunities in many industrial sectors. There is a trend toward miniaturizing devices, digitizing processes, increasing energy efficiency, reducing costs, and improving the quality of life. One of the key directions of this development is artificial intelligence, which finds applications in process automation, healthcare, and environmental monitoring. With increasing industrialization and technological advancement, the problem of air pollution is growing and poses a serious threat to human health and ecosystems. Particulate matter, smog, and exhaust emissions in urban environments contribute to climate change, environmental degradation, and respiratory ailments. In highly developed countries, pollution levels are particularly high, generating the need to implement advanced technologies for precise air quality monitoring [1]. Modern systems, such as intelligent environmental stations equipped with multi-parameter sensors, enable accurate, fast, and energy-efficient real-time measurements [2]. Integration with computer systems and artificial intelligence enables automatic data processing and analysis without user intervention. Such solutions are a key element of efforts to control and reduce harmful emissions, supporting the protection of public health and the environment.

In the face of growing demands for ecology and energy efficiency, the development of modern, energy-efficient, and easy-to-use measurement systems is essential. Analysis of available technologies, scientific literature, and standards such as WHO guidelines enables the design of devices that combine high measurement accuracy with functionality and reliability. In the context of building automation, such stations can play an important role in monitoring environmental parameters – such as air quality, temperature, and humidity – and in optimizing the operation of HVAC systems, contributing to improved occupant comfort and reduced energy consumption [3].

This chapter presents a proprietary concept for a smart air quality measurement station and an analysis of its operation, demonstrating the practical application of the ESP32 platform and cost-effective environmental sensors for monitoring environmental parameters.

ESP32 – open source hardware/software

Electronic devices, depending on their function, typically incorporate at least one control circuit responsible for controlling and coordinating the processes occurring within the system. However, not all designs require such a component – simpler solutions utilize only analog circuits, such as audio amplifiers or filters, or purely mechanical devices, such as clocks or switches. Modern electronic systems, particularly those designed for communication with the user, measuring environmental parameters, or implementing complex algorithms, utilize microcontrollers or microprocessors. These include smartphones, household appliances, building automation systems, and industrial controllers. In the presented project, the key element of the entire system is the microcontroller, responsible for its proper operation.

The selection of the control unit was based on an analysis of several key criteria. The most important was the presence of an integrated Wi-Fi module, enabling remote communication with the device via a local network or the Internet. This solution allows for easy transmission of measurement data to external servers for further analysis. After comparing available microcontrollers, we decided to use a chip from the ESP32 family from Espressif [4]. This choice was justified by its high computational performance, extensive programming support, low price, and built-in wireless connectivity. The ESP32-WROOM-32U module (Fig. 1) also features an IPEX connector for connecting an external antenna, significantly improving the stability and range of Wi-Fi communication.

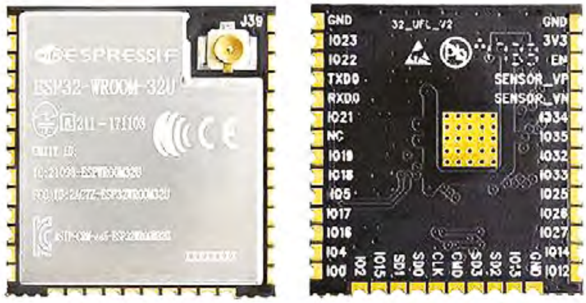

FIGURE 1. Appearance of the ESP32-WROOM-32U module [2]

Description of the structure and components of the measurement system

In the design process of any electronic device, a key step is the development of a custom electrical diagram, which specifies how all components are connected into a coherent and functional system. This diagram reflects the designer's operational concept and forms the basis for subsequent project implementation stages. Its accuracy is fundamental – even a minor error can lead to design flaws, which in mass production can generate significant financial losses. Design documentation should clearly present the device's structure and operating principle, which is particularly important when collaborating with the client, where a clear presentation of technical assumptions is essential. Another crucial element of the design process is the appropriate selection of electronic components, consistent with the functional requirements and parameters specified in the technical specifications.

Before commencing the actual design of the measurement system for the air quality monitoring system, an analysis of available electronic components was conducted. Among these, those that enabled the creation of a complete, efficient, and cost-effective measurement system were selected. The selection of components was based on project experience and an analysis of the technical literature. In order to verify the operation and accuracy of low-cost environmental sensors, a prototype test system based on the ESP32 microcontroller, equipped with temperature and gas sensors, was developed (Fig. 2).

The station's design was designed to ensure stable power supply and uniform current and voltage distribution to all system components. This approach minimizes interference and measurement errors during device operation. During the prototyping phase, breadboards were used to serve as a temporary mounting platform for electronic components. The final design was implemented on a pre-designed printed circuit board (PCB) measuring 8x7 cm, prepared in the EasyEDA engineering environment [5].

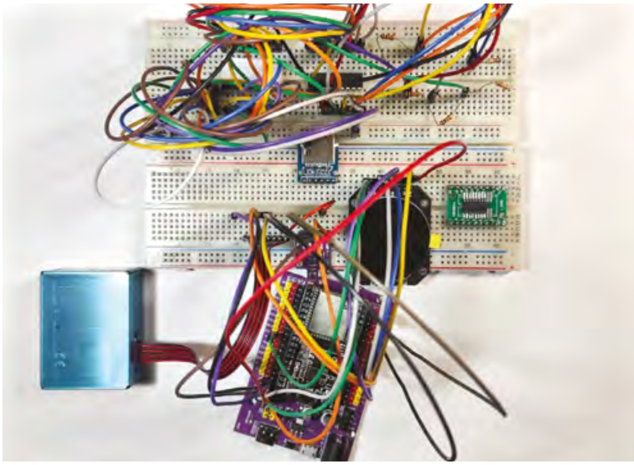

FIGURE 2. Prototype measurement system based on the ESP32 microcontroller

Male-to-male and female-to-male cables were used to connect the individual system components, enabling flexible and permanent connection of measurement elements. A popular AMS1117 linear voltage regulator [6] was used to ensure stable power supply for each sensor. The system's power source is a 9 V/3 A DC power supply, which supplies voltage in parallel to the microcontroller and regulator. The heart of the control system is an ESP32 microcontroller, powered by 3.3 V, responsible for the acquisition, processing, and transmission of measurement data. A 1.28" round TFT display [6] with a resolution of 240×240 px, based on IPS technology, was used to present the results, ensuring good readability and contrast.

The measurement module was equipped with BME680 [8] and PMS5003 [9] environmental sensors, enabling the measurement of temperature, humidity, pressure, volatile organic compounds, and suspended particulate matter. Additionally, the design included a TEMT6000 [10] light sensor, which automatically adjusts the screen brightness depending on the ambient light level, thus reducing power consumption. Each of the components used (Fig. 3) was individually tested before the measurements began. Additional small electronic components were also used to support the system's operation.

The BME680 temperature and humidity sensor was selected for the project because it is one of the most widely used and cost-effective environmental sensors in engineering applications. It is unique in its ability to simultaneously measure four basic air parameters: temperature, humidity, atmospheric pressure, and volatile organic compound (VOC) concentration. Additional parameters, such as carbon dioxide (CO_2) concentration and the air quality index (IAQ), are calculated programmatically based on dedicated algorithms.

The sensor, housed in a compact metal housing, is widely used in indoor air quality monitoring systems. Inside the sensor is a MOX (Metal Oxide Semiconductor) sensor, which detects VOCs by adsorption of molecules onto a metal oxide surface. Unlike many other detectors, the BME680 measures the combined level of all organic compounds, making it a non-specific sensor for individual gases but more versatile in general air quality analysis.

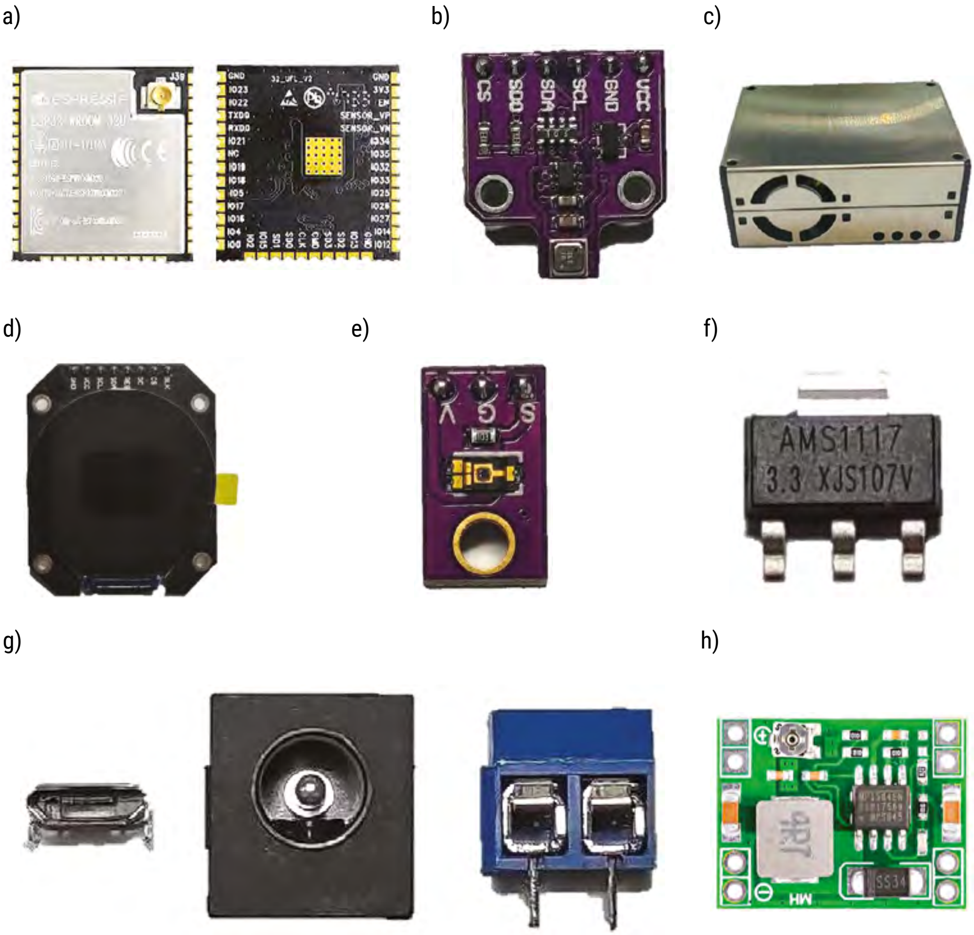

FIGURE 3. ESP32-WROOM-32U (a); BME680 (b); PMS5003 (c); 1.28" TFT display (d); TEMT6000 sensor (e); AMS1117 (f); power connectors used (g); converter (h)

The manufacturer, Bosch Sensortec, developed dedicated BSEC (Bosch Software Environmental Cluster) software [8] for this system, which includes a set of intelligent computational algorithms. It enables automatic determination of the air quality index (IAQ), estimation of VOC and CO_2 concentrations, and correction of environmental measurements. Thanks to its various operating modes, the sensor boasts very low power consumption – in power-saving mode, it consumes approximately 0.1 mA, while in standard mode, it consumes approximately 1 mA, allowing for efficient management of the entire system's energy budget.

The second important measurement element of the system is the PMS5003 sensor from Plantower, designed for the detection of suspended particulate matter using a laser (optical) method. This module combines small sizes with high measurement precision. Plantower specializes in the development and production of modern air quality sensors, ensuring reliable operation in industrial and consumer applications. The PMS5003 sensor utilizes a laser light scattering method, a patented hexagonal shielding structure, and enables real-time measurement [9].

The device's measurement range covers PM1.0, PM2.5, and PM10 dust fractions, with a particle size range of 0.3–10 μm, and a resolution of 1 $\mu g/m^3$. The PMS5003 sensor communicates with the ESP32 microcontroller via a UART interface, while the BME680 sensor uses an I^2C bus.

To fully illustrate the communication and data flow between the individual system components, a detailed block diagram (Fig. 4) was developed, which illustrates the operating logic of the smart measuring station and the interactions between the measurement modules and the microcontroller.

An electronic device should be housed in a properly designed enclosure that protects fragile electronic components. It provides a fundamental barrier against environmental factors and mechanical damage. A properly designed enclosure can also protect the device from dust, moisture, water, extreme temperatures, as well as electromagnetic interference (EMI) and radio frequency interference (RFI). Furthermore, it limits direct user access to live parts, improving operational safety.

After developing the printed circuit board (PCB) design, it was possible to begin designing an ergonomic and aesthetically pleasing enclosure. For this purpose, precise dimensional measurements of all electronic components, including the PCB, connectors, display, and sensors, were taken. This data was then transferred to a 3D CAD environment, where spatial modeling of individual components and their placement within the enclosure were performed.

This approach enabled the precise arrangement of components in three-dimensional space, optimizing the placement of mounting holes, buttons, communication ports, and ventilation openings. By transferring the actual dimensions of the electronic components to the digital model, it was possible to design a compact, functional, and easy-to-assemble enclosure (Fig. 5).

The Autodesk Fusion 360 environment [11] was used to create the proprietary 3D enclosure model, which was used for analysis, visualization, and verification of the design's ergonomics. This environment enables both parametric modeling and the creation of realistic visual renderings.

All housing components, except the transparent plexiglass cover, were 3D printed using FFF (Fused Filament Fabrication) technology. The prototype was manufactured using a biodegradable polymer – polylactide (PLA), which is low-cost, easy to process, and environmentally friendly. This material is widely used in engineering and educational projects due to its dimensional stability and the absence of a closed build chamber during printing.

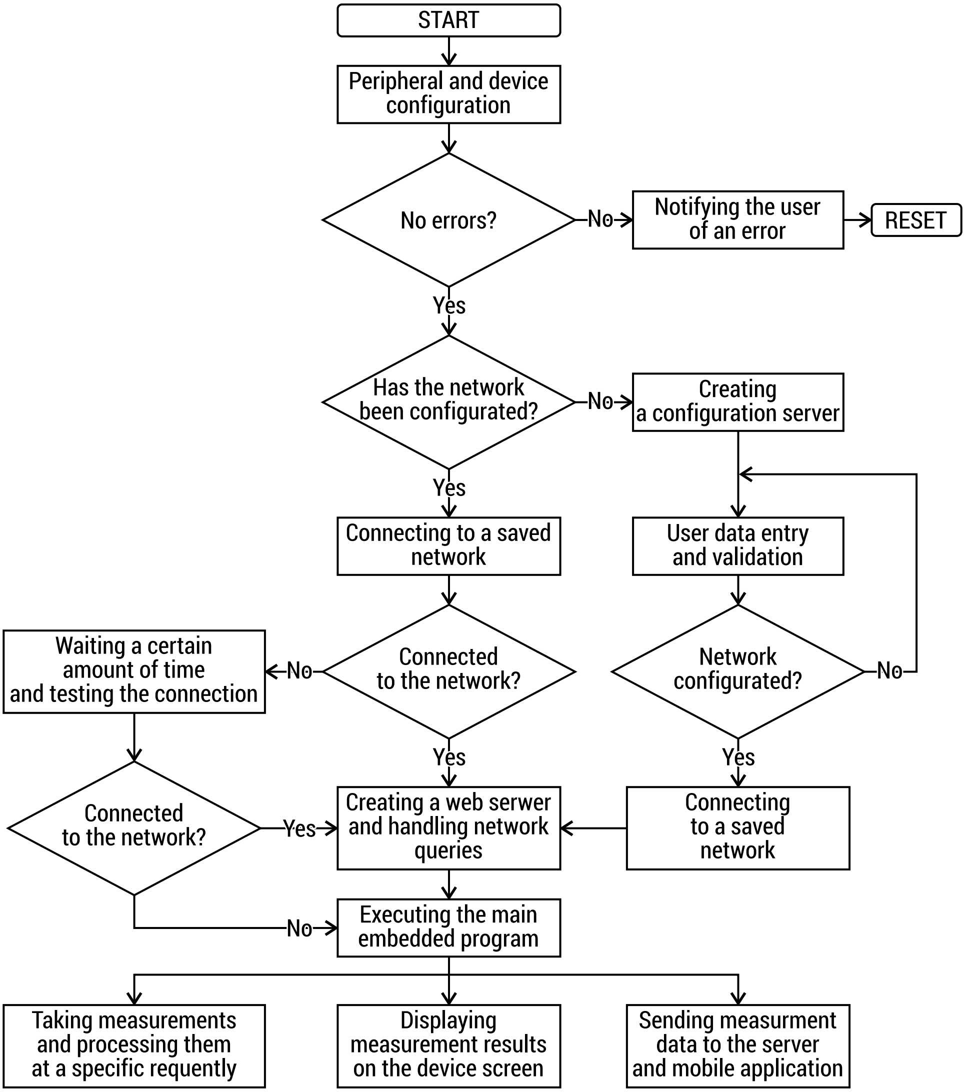

FIGURE 4. Block diagram of the measurement system program

The device is programmed to provide measurement data both locally – on the built-in TFT display and remotely via a dedicated mobile app for Android (version 5.0 and higher). This allows the user to monitor air parameters without the need for physical contact with the device, significantly improving user comfort. This solution allows for real-time readings of temperature, humidity, atmospheric pressure, VOC concentration, and particulate matter (PM) from anywhere within the local network range.

To ensure proper remote monitoring, the measuring station and the mobile device must be connected to the same Wi-Fi network, maintaining adequate signal strength throughout the entire user area (e.g. home, office, laboratory). This solution aligns with the principles of building automation systems (BAS), increasing their functionality and usability [12, 13].

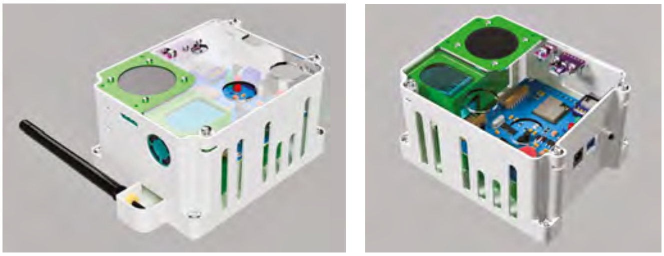

FIGURE 5. Three-dimensional model of the device (isometric views)

Fig. 6 presents screenshots of the complete, fully functional interface of the mobile application, enabling remote monitoring and visualization of environmental parameters. The application was developed using MIT App Inventor, a high-level visual programming language developed by the Massachusetts Institute of Technology (MIT) [14].

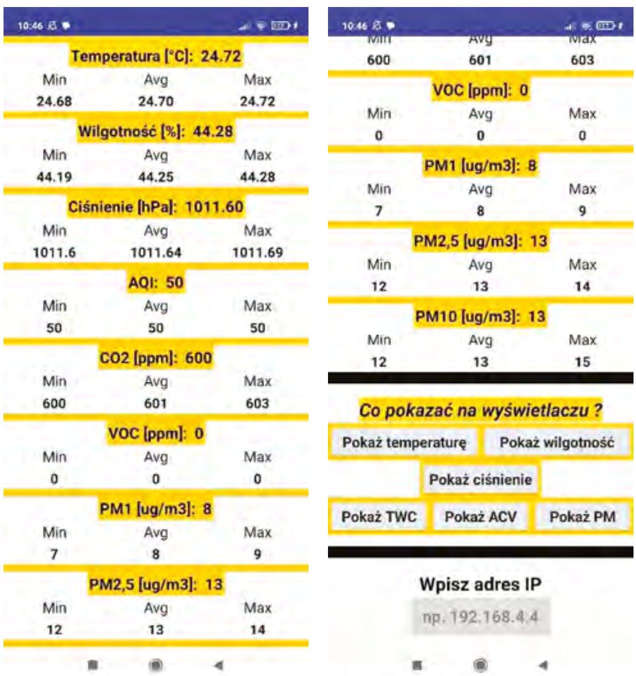

FIGURE 6. Graphical interface of the mobile application for an Android smartphone

Devices designed for monitoring air parameters should be able to communicate with the Internet, enabling remote access to measurement data and central management of results without the need for physical presence at the device. This solution significantly enhances the system's functionality and allows for integration with other IoT infrastructure components.

As part of the project, an ESP32 microcontroller was programmed to transmit measurement data to the ThingSpeak cloud platform, developed by MathWorks (Fig. 7) [15]. This platform enables automatic recording, analysis, and visualization of results in real time, enabling continuous monitoring of environmental changes. Data is presented in the form of dynamic graphs, updated without user intervention, eliminating the need for manual reading and archiving.

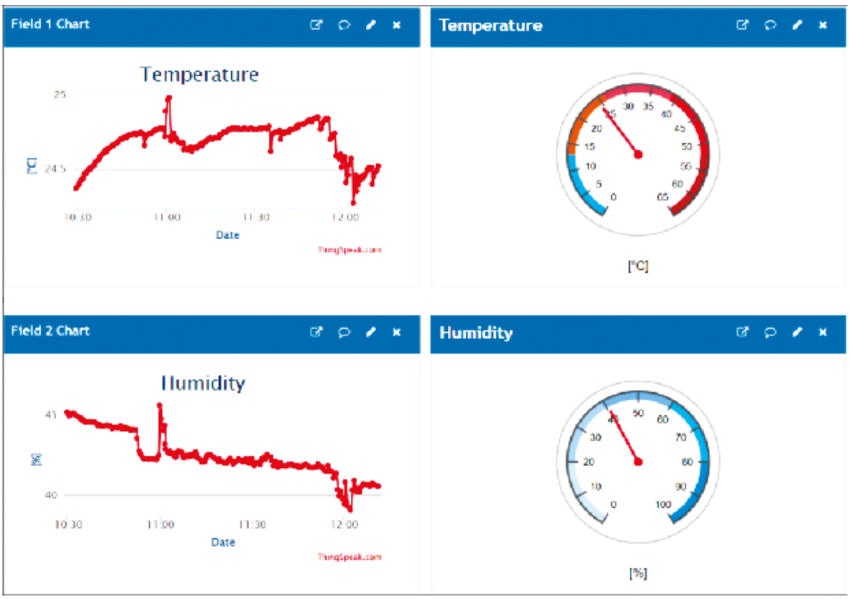

FIGURE 7. Example visualization of air temperature and humidity using a graph and a circular gauge

An additional advantage of this solution is the ability to remotely access data from any mobile device or computer, regardless of the network to which the measurement station is connected. This allows users to monitor measurement results from anywhere, which is particularly important in home, educational, and industrial applications.

After building the entire system, it was decided to perform some measurements and check the correct operation of the program (Fig. 8).

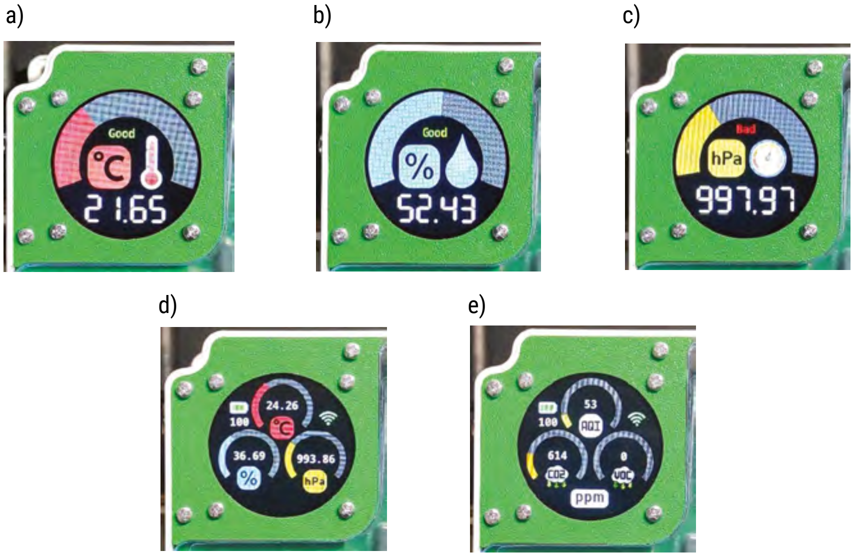

FIGURE 8. Photo illustrating the display of selected parameters of the BME680 sensor on a physical device: a) temperature; b) humidity; c) atmospheric pressure; d) a summary of the three mentioned parameters; e) a summary of the AQI, CO_2 and VOC parameters

Analysis of results

To assess the correct operation of the designed measurement system, tests were conducted in an environment with dynamically changing air parameters. The tests were conducted in a residential room with an area of approximately 20 m^2 and a volume of 54 m^3. The device operated continuously for 24 hours, placed at a fixed measurement point to ensure repeatable test conditions. All measurement data was transmitted in real time via Wi-Fi to the ThingSpeak platform, where it was analyzed and visualized. Prior to the actual measurement, the device underwent a 48-hour calibration, which allowed the sensors to stabilize and obtain reliable results.

Fig. 9 presents the temperature, relative humidity, and atmospheric pressure measurement results recorded during the experiment. The data indicates the correct and stable operation of the measurement system and the high sensitivity of the sensors to environmental changes. Natural fluctuations in values were observed during the study period, resulting from typical indoor activities, such as opening windows or changing microclimate conditions.

Preliminary results confirm that the designed system operates correctly and meets its functional requirements, providing reliable measurement of basic indoor air parameters. Further research is planned with an expanded scope – including measurement of gaseous pollutants and suspended particulate matter – to fully verify the performance of the developed device.

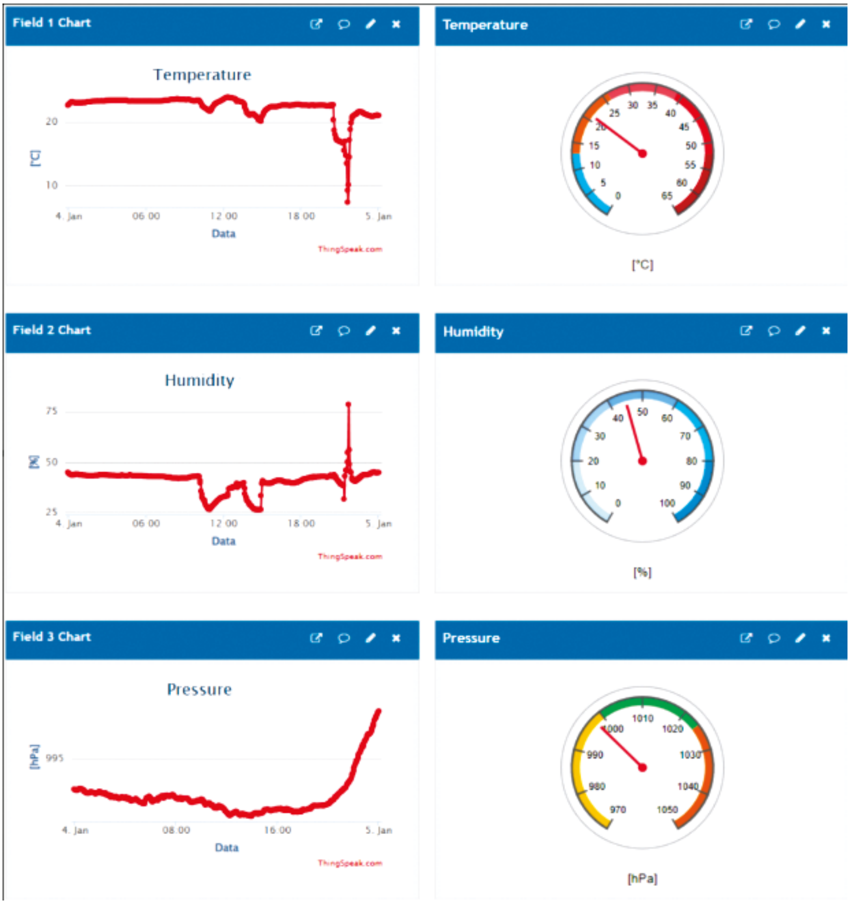

FIGURE 9. Temperature, humidity and pressure measurements in a dynamic environment

Future research phases will expand the scope of testing to include measurements of additional air quality parameters, such as carbon dioxide (CO_2) concentration, volatile organic compounds (VOCs), and the relative humidity index (AQI). Additionally, the device will be analyzed for its accuracy in detecting suspended particulate matter of various granularities – PM1.0, PM2.5, and PM10 [16]. This will allow for a comprehensive assessment of the system's effectiveness in monitoring the indoor environment and its response to changing ambient conditions. The planned experiment will be conducted in an environment corresponding to typical office work conditions. The aim will be to replicate natural changes in air quality resulting from everyday activities, such as the presence of people, the use of office equipment, and room ventilation. Test conditions will be maintained in a room with an area of approximately 8 m^2 and a volume of 22 m^3, equipped with standard office furniture and equipment. Measurements will be conducted between 10:00 AM and 8:00 PM, allowing for the recording of a full daily activity cycle. Initial preparations will include a 48-hour calibration of the device under reference conditions, according to a previously developed procedure.

Previous prototype tests have already confirmed the high effectiveness of the developed system, both in terms of measurement stability and the accuracy of recorded data. The device demonstrated its ability to operate reliably in continuous mode and respond immediately to changes in air quality. When combined with the ThingSpeak platform, measurement results are presented in real time, making the system a fully functional IoT solution. The planned expansion of the tests will not only allow for the validation of the accuracy of individual sensors but also for a comprehensive assessment of the device's practical usefulness in various environments – from office to residential.

Summary and conclusions

This article presents a proprietary design for a compact measuring station designed for precise monitoring of environmental parameters. The device records key meteorological data such as temperature, humidity, atmospheric pressure, and air quality indicators (including particulate matter and VOCs). The obtained results confirmed the high accuracy and stability of the sensors, demonstrating the effectiveness of the developed measurement concept.

The system was designed for integration with IoT platforms and modern building automation systems. This enables automatic control of ventilation, heating, or air conditioning based on actual ambient conditions, resulting in greater user comfort and more efficient energy management. Access to data via a web-based analytical platform enables real-time visualization and remote monitoring from any location.

In summary, the developed measuring station represents a modern and flexible IoT solution that can be used in both smart buildings and standalone environmental monitoring systems. Further development work will include increased structural robustness, calibration precision, and module miniaturization, enabling even broader application of the developed technology in practical applications.

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