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State of the art review on air quality monitoring

Streszczenie. *W artykule przedstawiono szeroki przegląd zanieczyszczeń powietrza występujących głównie w środowiskach miejskich. Począwszy od lotnych związków organicznych (LZO), a skończywszy na stężeniu cząstek stałych (PM). Omówiono główne cechy zanieczyszczeń powietrza i obszary ich występowania. Szczególną uwagę zwrócono na dopuszczalne zakresy występujących zanieczyszczeń, omawiając główne zalecenia normatywne UE/WHO. Główny obszar przeglądu stanu wiedzy w zakresie monitoringu zanieczyszczeń powietrza ograniczono do ostatnich kilku lat. Wskazany kierunek rozwoju nowoczesnych systemów pomiarowych w kierunku tanich czujników pracujących w strukturach Internetu Rzeczy odzwierciedla najnowsze trendy rozwojowe w monitorowaniu parametrów klimatycznych.* (**Stan wiedzy w dziedzinie monitoringu jakości powietrza)**

Abstract. *This article gives a broad overview of common air pollutants mainly occurring in metropolitan environments. Starting from volatile organic compounds (VOCs) and ending with particles matter concentration (PM). The main characteristics of air pollutants and areas of occurrence are discussed. Special attention was given to the acceptable ranges of occurring contaminants by discussing the main EU/WHO normative recommendations. The main area of review of the state of the art in air pollution monitoring was limited to the last few years. The shown direction of development of modern measurement systems towards low-cost sensors working in the structures of the Internet of Things reflects the latest development trends in monitoring of climatic parameters.*

Słowa kluczowe: zanieczyszczenia powietrza, zarządzanie środowiskiem, parametry klimatyczne, czujniki, systemy bezprzewodowe.
Keywords: air pollutants, environmental management, climate parameters, sensors, wireless systems.

Introduction

The issue of monitoring environmental parameters is the subject of continuous work in major research centres around the world. The increasing level of pollution causes that the standards set by various world organisations are sometimes exceeded many times over. The degree of urbanisation and the lack of modern technologies limiting the emission of various types of pollution, contribute to the deepening of the problem of pollution of the natural human environment. The activities undertaken are focused on two main objectives. Firstly, energy-saving and low-emission generation technologies are being developed and, secondly, measurement networks are being built to monitor the degree of environmental contamination. On the basis of this research work, a number of standards and recommendations have been developed with the aim of reducing the progressive contamination of the planet. Many of the standards developed so far were limited to a relatively narrow group of air pollutants that were recommended to be monitored. Within the framework of the presented article, an attempt was made to systematise the current state of recommendations and legal regulations concerning air pollution by analysing the majority of naturally occurring gases. The presented and characterised set, in the authors' opinion, is sufficient for the time being. Sensors used in measurements are a separate problem. The dynamic development of both technology and means of data transmission has significantly contributed to the development of measurement systems more and more effective and cheaper, and thus more easily accessible. The current state of work shows completely new trends focusing on the possibility of replacing expensive and very complicated measurement stations with much simpler and cheaper sensor measurement nodes. There are dozens of studies in the literature comparing various sensors and measurement methods. A common disadvantage of such publications is their quick obsolescence being the effect of continuous development. The authors of this article decided to focus on presenting the main development trends in the field of construction and application of sensors used in air monitoring. In order to match the quality and accuracy of the measurements made, a number of procedures and measurement algorithms have been developed that provide results comparable to those of high quality measurement stations. Undoubtedly, such a trend favours the development of relatively cheap early warning systems or effective forecasts of the occurrence and movement of air pollution. The last few years have seen equally dynamic development of information technologies for the transmission and analysis of measurement data. A good example of this is the Internet of Things technology, which has recently become a very popular IT tool. A number of low-cost dedicated hardware and IT platforms have been developed that allow complex signal processing and analysis algorithms to be implemented at relatively low cost.

Air contamination in open and closed spaces

The problem of monitoring basic climate parameters is the subject of a wide range of currently conducted works. The ongoing work aims to define a set of optimal values that have a significant impact on human health. Modern measurement of basic climate parameters is carried out both in open and closed spaces. Particular attention is paid to air quality in public buildings. This set of parameters is very broad, ranging from basic parameters such as temperature, humidity, pressure, wind force and direction, to PM concentration measurements for two sizes of 2.5 and 10 micrometers [1 - 4]. In many countries there are a number of legal regulations concerning both indoor and outdoor climate conditions. European regulations and standards can be divided into two main groups. The first of these are European Union directives, which are regulations in force in the Member States, the enforcement of which is legally formalized. This means that it is for the Member States to take them into account in their national law. The second group of standards and regulations are all acts published by health organizations that issue recommendations regarding indoor air climate parameters. They are not binding but constitute important guidelines for companies and individuals who place great emphasis on pro-health activities [5,6].

The basic directive is the European Council Directive of 30 November 1989 concerning the minimum safety and health requirements for the workplace (first individual Directive within the meaning of Article 16 (1) of Directive 89/391 / EEC and 89/654 / EEC). The most important European standard is EN 13779: 2007. It is a European standard that focuses on achieving a comfortable and healthy indoor environment in all seasons, considering the economy of installation and operation. It is now the national standard in all EU Member States. The standard classifies indoor air quality from IDA 4 (low air quality) to IDA 1 (high air quality). The method of determining the level of air quality is testing the carbon dioxide content. On this basis, Table 1 gives typical ranges for CO_2 levels in ppm and recommended values for added outdoor air to achieve different indoor air quality categories. It should be noted that this method does not consider the gaseous pollutants introduced into the building by means of outdoor air.

Table 1. Indoor air quality classification Category

Cate-gory	*Description*	Description CO_2 concentration above the value found in the fresh air (approx. 400 ppm)	Air exchange rate (m^3/h) person)
IDA 1	High IAQ index	< 400	> 54
IDA 2	Medium IAQ index	400 – 600	36 - 54
IDA 3	Moderate IAQ index	600 - 1000	22 – 36
IDA 4	Low IAQ index	> 1000	< 22

Considering the ECA (European Collaborative Action) report, it is possible to assume the optimal conditions that should be provided in offices [7]. The maximum recommended CO_2 concentration for a comfortable human stay was set at 800 ppm. The maximum allowable concentration for short-term residence was set at 2500 ppm. Temperatures for a comfortable stay for humans range from 18 to 28 °C and humidity from 30 to 70% RH, depending on the external climate and season. Ultimately, after analyzing all regulations, standards, and studies of the impact on human health, the following ranges of impact on human health and comfort were adopted (Table 2).

When analyzing the main air pollutants caused by natural phenomena or human activity, ten types should be considered, they are: sulfur dioxide, carbon monoxide, carbon dioxide, nitrogen oxides, volatile organic compounds (VOC), solid particles, ozone, chlorofluorocarbons (CFCs), unburned hydrocarbons lead and heavy metals. In the case of natural pollution sources, the analysis covers PM carried by wind from places with very little or no green cover, gases released as a result of natural processes of living organisms, fumes from burning various flammable objects, volcanic eruptions, etc. [8].

Table 2. Ranges of impact on human health and comfort

Air quality	Tempe-rature range (°C)	Humidity range (% RH)	CO_2 concentra-tion range (ppm)
Optimal (comfortable)	20 - 24	40 – 60	400 – 1000
Permissible (medium noxiousness)	18 – 20 24 – 27	30 – 40 60 – 70	1000 – 2000
Not allowed (harmful to human health)	<18 >27	<30 >70	> 2000

Due to intensive human activity, we are dealing with two groups of pollution sources: sources of external pollution and sources of indoor pollution.

For indoor pollution sources, one of the main sources is the combustion of fuels such as manure, coal and wood in inefficient furnaces or furnaces, which produces a variety of pollutants that are harmful to health. These include carbon monoxide, methane, particulate matter (PM), polyaromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs). VOCs are water-soluble compounds and have a low vapor pressure. Many volatile organic compounds are chemicals that are used in the manufacture of paints, pharmaceuticals, and various types of coolants. VOCs are typically industrial solvents such as trichlorethylene, oxidized fuel products such as methyl tert-butyl ether (MTBE); or by-products from water treatment such as chloroform. Volatile Organic Compounds (VOCs) are often found in fuel oils, hydraulic fluids, paint thinners and dry-cleaning products. VOCs are common groundwater contaminants. Volatile organic compounds (VOCs) are released as gaseous gases by some liquids or solids. VOCs include a wide range of chemicals, some of which can have short and long-term adverse health effects [9]. Many VOC concentrations indoors are up to ten times higher than outdoors. The source of (VOC) are dozens of products found in everyday life. Examples include paints, varnishes, paint removers, cleaners, pesticides, building materials, furniture, office equipment such as copiers and printers, correctors, carbon-free papers, graphics, and creative materials, including permanent markers, photo solutions and adhesives. Organic chemicals are commonly used in home furniture. Paints, varnishes, and waxes contain organic solvents, as do many cleanings, disinfecting, cosmetic, degreasing and hobby products. Fuel is produced from organic chemicals. organic compounds may be released from these products during use and to some extent during storage. The recommended VOC levels in the air are provided by several organizations such as the National Institute for Occupational Safety & Health (NIOSH), the European Agency for Safety and Health at Work (OSHA), the American Conference of Governmental Industrial Hygienists (ACGIH) and the French Agency for Food, Environmental and Occupational Health & Safety (ANSES). The list of permissible concentrations of selected VOCs is presented in Table 3.

According to the WHO reports [10], 91 % of the population lives in conditions where air contamination exceeds acceptable levels. List of air pollution that has the greatest impact on human health is shown in Table 4.

Table 3. The list of permissible concentrations of selected VOCs.

VOCs	NIOSH recommended exposure limit (ppm)	OSHA permissible exposure limit (ppm)	ACGIH threshold limit value (ppm)	ANSES (VGAI) long exposure (ppm)
Benzene	0.1	1	0.5	0.0006
Toluene	100	200	20	5.31
Ethylbenzene	10	10	10	0.345
Xylene (m-o-p-)	100	100	100	-
Formaldehyde	0.016	0.75	0.3	0.024
Acetone	250	1000	250	-
Ethanol	1000	1000	1000	-
Methanol	200	200	250	-
Isopropanol	400	400	200	-

Table 4. Limits of air pollution in atmosphere according to EU/WHO

Name substances	EU / WHO limits	Source of pollution
SO_2	40 µg/m^3 24-hour mean	Combustion of coal
NO_2	10 µg/m^3 annual mean 25 µg/m^3 24-hour mean	Combustion of fossil fuels, energetics, road transport
PM10	15 µg/m^3 annual mean 45 µg/m^3 24-hour mean	Combustion of fossil fuels, incomplete combustion of fuels, road transport volcanic eruptions, erosion of the crust
PM2.5	5 µg/m^3 annual mean 15 µg/m^3 24-hour mean	
CO	10 mg/m^3 8-hour daily maximum	Combustion of fossil fuels, energetics, road transport
Ozone	100 µg/m^3 8-hour daily maximum 60 µg/m^3 8-hour mean, peak season	Derivative pollution of road transport
Benzene	5 µg/m^3 annual mean	Combustion of high energetic fuels, road transport
Benzo (A) pyrene	1 ng / m^3 annual mean	Incomplete combustion of fuels, combustion of waste

From the point of view of large urban agglomerations, the level of PM in the environment caused by burning solid fuels and road transport is very important. One of the most important components of air pollution is PM. It consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. The particle diameter is classified into three basic fractions: PM 10 - with the aerodynamic diameter of the grains smaller than 10 µm, PM 2.5 and PM 1.0, with aerodynamic diameters smaller than 2.5 and 1.0 µm, respectively. Particulate matter is a serious human pathogen. It enters the human body through two routes: respiratory or digestive. PM with an aerodynamic diameter below 10 µm enter the respiratory tract with the inhaled air, which can cause allergic and inflammatory reactions. Particles with an aerodynamic diameter below 2.5 µm are more harmful to health as they enter deeper parts of the body. They can reach the alveoli, obstructing gas exchange. Particles below 0.1 µm can penetrate from the alveoli into the blood vessels and through the blood system to organs and tissues [7,9].

In summary, measurement of air quality in terms of chemical contamination and PM is a subject all the time and being the subject of current research in many research centers around the world. This is especially important in areas where solid fuels are used to meet the vital needs of the population [11]. However, air quality considerations are common to all places in the world, especially in urban areas, offices, and housings. This overview provides a quick and single overview of the most common hazards and regulations showing threshold values for a number of contaminants. It provides a very good starting point for designing a monitoring network whether it is for early warning or as a signal source for modern heating, ventilation, air conditioning (HVAC) systems.

State of art

Air quality monitoring sensors and systems are rapidly gaining popularity due to concerns about increasing air pollution and the spread of pollutants both indoors and outdoors. This is further influenced by the tragic experience of the coronavirus pandemic (COVID-19), which has put the issue of air quality in the spotlight worldwide.

The growing availability of an array of sensors for air quality monitoring provides an opportunity to design and prototype custom, low-cost sensor (LCS) and dedicated low cost multisensor platforms (LCSS). [12]

The measurement of air quality in both open and closed spaces is presented in many international publications. Analysing the current work, two main streams can be distinguished. The first stream concerns monitoring of air contamination in open spaces for the needs of environmental protection services, the second stream is focused on providing data for modern building air conditioning and ventilation systems. In many cases, the overall system uses Internet of Things (IoT) technology to control and manage large assemblies of measurement devices.

The main problem related to the use of LCS sensors is their accuracy and repeatability. Many ongoing research works show that in many cases it is possible to replace professional measuring stations with LCS sensors supported by appropriate algorithms for processing the obtained results.

Paper [13] presents a study of air quality LCSS systems at four locations in Australia and China. The systems tested included sensors, for PM 2.5 (Plantower PMS1003), Alphasense CO-B4 for carbon monoxide, CO and LCSS KOALA. The tests confirmed the effectiveness of the sensors used and their long-term quality.

The paper [14] provides guidelines for end-users for the effective implementation of low-cost air pollution monitoring sensors. The characteristics of several low-cost PM and gas sensors are given as an example and recommendations for end-users for their proper selection are defined.

Low-cost sensor networks are very sensitive to the influence of external factors such as traffic, weather changes or typical human behaviour. The paper [15] shows the possibility of improving the quality of measurements by applying periodic calibration using machine learning techniques. In many situations, the heterogeneity of air pollution both in time and space makes proper monitoring difficult. Crowdsensing, which includes local pollutant concentrations as well as the location and mobility of people in the analysis, can be a preventive measure. Compared to traditional static monitoring, it avoids misclassification of exposure to air pollutants [16].

The issue of LCS use in air pollution monitoring is the subject of research conducted under the auspices of European Union agencies. The report [17] analyses over 100 measurement systems based on LCS networks. The presented analyses utilised work carried out at, among others, the California Board - Air Quality Sensor Performance Evaluation Center (AQ-SPEC), the European Union Joint Research Centre (EU JRC) and the United States Environmental Protection Agency (US EPA). The paper focuses on comparing the agreement between measurements made with the LCS and reference measurements, assessing the availability of raw data, the transparency of data processing and the possibility of a posteriori calibration. The ability to measure multiple pollutants and the affordability of the sensor systems were also analysed, taking into account the number of sensors provided.

An interesting approach to the use of LCS in air monitoring is presented in a paper [18] where three low-cost laser sensors for measuring PM concentrations were evaluated against the standard Metone Aerocet 531s equipment, which is designed to measure oxygen concentrations in air. The sensors used in this study were PMS5003 (Plantower), SPS30 (Sesirion), SM-UART-04L (Amphenol). It is shown that the use of periodic calibration achieves comparable measurement accuracies.

The paper [19] present a qualitative and quantitative evaluation of low-cost sensors, while proposing a number of criteria for selecting sensors for a given application. An interesting analysis of measurement data from electrochemical gas sensors used in air quality monitoring systems is presented in [20]. The paper presents the possibility to perform predictive maintenance based only on calibration data, thus detecting the optimal moment to perform recalibration. In the paper [21], the authors present the possibility of integrating different types of measurement systems for air quality monitoring. The authors propose the integration of ground-based systems and satellite remote sensing systems supported by the latest information technologies. A similar theme is presented in paper [22] where the possibility of using LCSs to complement existing reference systems is described. Examples are given from the New York and Portland areas in the USA. Similar studies conducted in Seoul and Busan, Korea [23] have shown that commercially available low-cost O_3, CO, NO_2 sensors have great potential as monitors for short-term air quality studies in urban areas, at least for one-month periods. For longer periods, recalibration and post-processing is required

The paper [24] compared the effectiveness of several field calibration methods for low-cost sensors, including linear/multilinear regression and supervised learning techniques. Ozone, nitrogen dioxide, nitric oxide, carbon monoxide and carbon dioxide sensors were used in the study.

The paper [25] presents a developed low-cost measurement station for monitoring CO, CO_2, NO_2, O_3, VOC, PM2.5 and PM10 concentrations. All sensors were integrated on an Arduino Shield compatible board. A validation carried out over several months gave surprisingly good results, with no failures or sensor drift observed.

Territorially distributed air quality monitoring systems are a very good example to apply Internet of Things (IoT) technologies. The paper [26] presents a low-cost indoor air quality monitoring sensor using the hardware structure recommended by the Web of Things Working Group. The proposed sensor runs a web server on a system-on-chip microcontroller with low power consumption. The system records measurements of temperature, relative humidity, and carbon dioxide. Any HTTP capable client on the Internet can access this sensor, making it compatible with any air quality monitoring platform that uses HTTP.

The vast majority of contemporary wireless air parameter monitoring systems operate in real time. The paper [27] presents a system that monitors air quality in confined spaces. In addition to temperature and relative humidity, the system measures the concentration of CO_2, CO, SO_2, NO_2, O_3, Cl_2. The system is adapted to an open-source Internet-of-Things (IoT) platform called Emoncms for ongoing monitoring and long-term storage of collected data.

A good example of the work being carried out is the publication presented by Floris et al. [28] They have built an IoT-based system for smart buildings that enable measurement of total volatile organic compounds (TVOC) and equivalent carbon dioxide. They observed that recent pandemic events promoted the need to apply advanced measurement techniques to spaces occupied by people. Paper claims that new balance between increased energy consumption by *heating*, ventilation, *air conditioning* (HVAC) systems due to higher demand for fresh air and the quality of this air must be found. Similar observations are present in the very recent publication by Meng Kong et al. who meticulously analysed HVAC energy savings in several scenarios [29]. Their investigation included surveys obtained from nearly 500 people so that it not only relies on raw sensory data, computational system employing neural network but also on subjective opinion of the building users.

Another approach that considers air quality and power demand of HVAC systems was presented by Yu Yang et al. [30]. Their contribution has strong mathematical and algorithmically background. They observed that control of typical office building multiple zones with central HVAC unit is a NP-hard problem.

An interesting study was presented by Jun Ho Jo et al. as they implemented IoT-based air quality measurement system in subway of South Korean city Incheon [31]. Their findings prove that such system can provide insight to degradation of air quality in the presence of large number of commuters. Their research also shown that depth of subway tunnels correlates with worse air quality.

Cost-saving solution for air quality measurement system employing IoT concept was assembled by Minqiu Zhou et al. [32]. Their measurement system is simply based on inexpensive off-the-shelf components such as Arduino Leonardo. Despite its simplicity the system provides real-time measurements of air quality index using user-friendly online dashboard.

The article [33] discusses a monitoring station that allows the measurement of temperature, humidity, CO, PM10, and VOC. An interesting solution is to equip the station with three independent radio interfaces allowing communication to transfer measurement data (Wi-Fi), configuration (Bluetooth) and cooperation with the building network (RF). Based on the collected data, a current AQI of the indoor air in the building is created.

Mois et al. [34], present a station based on the energy efficient CYW43012 controller from Cypress Semiconductor enabling measurement of the above-mentioned quantities in addition to dust. It is noteworthy that the station, thanks to the use of two 27x7 mm amorphous solar panels, is energy self-sufficient both in outdoor and indoor conditions. In turn, Michalak [35] presents a system for measuring floor and indoor air temperature whose measuring nodes use a low-cost Atmega644PA controller and DHT11 and DS18B20 sensors,

Ha at al. developed a very advanced station allowing to measure concentration of: (hydrogen (H_2), ammonia (NH_3), ethanol (C_2H_6O), hydrogen sulfide (H_2S), and toluene (C_7H_8)), as well as CO, CO_2, O_2, and temperature and humidity [36]. The paper [37] presents the concept of a portable meter for carbon dioxide (CO_2), sulphur dioxide (SO_2), volatile organic compounds (VOCs), temperature and humidity and the presence of dust. The system will alert the user if the levels of these gases are exceeded by a Wi-Fi module in a smartphone.

Developments in information technology are also evident in LCSS., An example of this is the work of [38]. The paper presents a novel method for monitoring indoor air quality based on a network of 10 smart sensors permanently connected to the cloud. Each smart sensor was able to measure air temperature, relative humidity, particle concentration and carbon dioxide concentration. The paper [39] presents an air quality measurement system that consists of a distributed network of sensors connected to a cloud system forming a wireless sensor network. The sensor nodes use the low-power ZigBee data communication protocol and transmit measurement data to the cloud via a gateway. An optimised cloud system has been implemented to store, monitor, process and visualise the data received from the sensor network. Data processing and analysis is performed in the cloud using artificial intelligence techniques. Laboratory tests have confirmed the ability to detect some common VOCs, including benzene, toluene, ethylbenzene, and xylene. A support vector machine was used in the data analysis.

A classical approach to wireless sensor networks monitoring air parameters is presented in the article [40]. ZigBee modules were used here to connect the individual sensors to the control module, and then using GSM the data is transmitted to the monitoring centre.

The problem of signal transmission in wireless sensor networks, especially for air quality monitoring, is very important. An interesting solution is presented in the work [41], where LoRa communication is used. The proposed system is divided into two parts, an inner cluster, and an outer cluster. Each indoor sensor node can receive information about temperature, humidity, air quality, dust concentration in the air and send it to the Dragino LoRa gateway. The outdoor sensor nodes have the same functionality, adding solar power capability and are waterproof.

The paper [42] shows an interesting way of using a light scattering sensor to measure PM2.5, temperature, and humidity. The monitoring data is sent to mobile end devices or a PC terminal via Wi-Fi. The whole measurement system works using IoT technology.

The problem of error identification in territorially distributed measurement networks, especially in the case of air quality monitoring, is one of the biggest challenges for designers. An interesting solution was proposed in the work [43]. The proposed solution is based on the modified Kernel Partial Least Squares method. The effect of the proposed modifications provides both reduced computation time and false alarm rate.

Data integrity and security of the system used for air quality monitoring are rarely considered when designing and implementing such systems. This results in a huge scope for unwanted and harmful cyber intrusions. The paper [44] presents an analysis of low-cost air quality monitoring systems. The results obtained confirm the urgent need to improve the security and data integrity of these systems.

Analysing the construction of stations and systems, one can see a trend of minimizing the recommended measurement methods in favour of an increased number of low-cost and energy-efficient measurement stations based on sensors of sufficient measurement quality.

Taking into account the wide spectrum of monitored pollutants, it is necessary to use various measurement methods. Depending on the measured parameter, the optimal method is selected. We can distinguish several basic methods: electrochemical, electronic, optical, and surface acoustic wave (SAW).

The principle of operation of an electrochemical sensor is based on changes in the electrical parameters of the electrodes in contact with the electrolyte in the presence of a specific gas. The change in electrical parameters is the result of a redox chemical reaction (reduction / oxidation) of the measured gas on the electrode surface.

Electronic sensors use the influence of external conditions on the parameter of the electric circuit of a given sensor, e.g., resistance. In a further step, this parameter is converted into a unified electrical signal.

Optical sensors use the absorption or scattering of the optical ray by molecules or particles of the measured medium. The most common source of the optical beam is the laser. Sensors operating based on the phenomena accompanying the propagation of surface acoustic waves (SAW), enable the detection of the presence of selected chemical compounds. The term SAW covers a whole range of waves propagating within the subsurface layer of solids or at the contact of the surface of solids with other media. The principle of the SAW electrochemical sensor is to change the parameters of the substrate generating the surface wave as a result of the interaction of the molecules of the measured chemical substance. In all cases, information about changes in the environment is manifested in a change in the speed, period, or amplitude of the induced wave.

Among the measured environmental parameters, the greatest problem is the measurement of the concentration of suspended dust PM 2.5 and PM 10. Measurement methods of PM concentration are known and can be divided into analytical and optical methods. The reference analytical method of PM concentration, according to EN 12341:2014 standard, is the gravimetric method [24, 45, 46]. In this method, a sample of measured air flows at controlled volume flow (2.3 m^3/h), through the air track. A filter is placed in the cross section of the track, on which the PM fractions are deposited. The PM concentration is determined by measuring the weight of the filter before and after exposure. The filters are exposed for a precisely defined period of time, normally 24 hours. Filter replacement in the station is done automatically. Mass measurement is performed under laboratory conditions. The concentration (Cm) is calculated according to the relation (1)

$$Cm = (mload - mclear)/qt, \tag{1}$$

where: mload - mass of load filter, mclear - mass of clear filter, q - volumetric load, t - time of exposition.

Additionally, by analyzing the collected PM, we can determine the composition of PM contaminants. In practical measurements, three basic methods of measuring PM concentration are used, they are: absorption of beta rays by PM particles, Tapered Element Oscillating Microbalance (TEOM) and optical methods.

The first method is based on the absorption of beta rays by PM collected on a filter [47]. The beta rays are generated by a radioactive source which is carbon isotope 14C, inside the monitor. In the TEOM method, particles in the air at the entrance to the system are separated by a size filter separating the appropriate fraction. They then go to a filter placed on the oscillation system. They then reach a filter placed on top of a tapered oscillating system. The system is excited to oscillate continuously with the same energy, which causes it to oscillate at its natural frequency. The natural frequency of vibrations depends on the mass of the system, including the filter. An increase in the mass of deposited PM results in a change of the vibration frequency, which is continuously monitored [48]. Optical methods for measuring PM concentrations are not reference methods. However, a real-time PM monitoring system can be created only on the basis of these methods. Optical methods use the effect of light scattering on particles with dimensions close to the wavelength of the scattered light. This is described by the Mie scattering theory. Particulate mass concentration is calculated by converting the number of particles measured per unit time to mass per unit volume using dedicated multiple regression or from fixed particle densities.

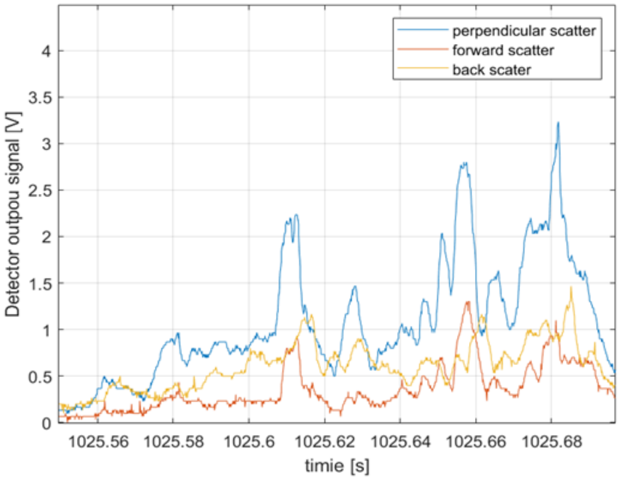

Fig.1. Signal frame perpendicular, forward, and back sensors during particles detected.

One of the PM sensors whose application was considered, was the system developed by Makowski et al in [49]. This sensor consists of a 5-mW red laser 660 nm. The system is based on a proprietary wind tunnel that ensures laminar flow (Reynolds number Re=2300) and a system of three light sensors. The sensors are placed perpendicularly and at angle 45 and - 45 in relation to the laser beam. This allows simultaneous measurement of light scattered in perpendicular, backward, and forward effects. This provides opportunities for better size selection of particles suspended in the tested aerosol. Exemplary signals obtained from sensors during particles detected are presented on Figure 1. Real construction of sensor is presented on Figure 2. While the measurements of PM concentration are a big challenge, the measurements of other parameters are a standard solution used in industrial measurements.

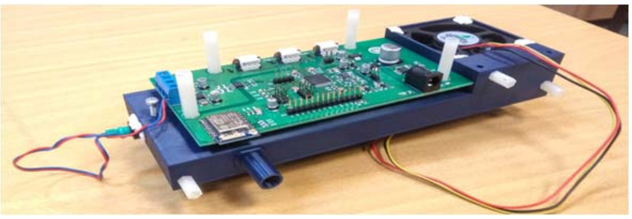

Fig.2. Real construction of sensor made by Makowski and Dziadak [30].

The last decade has seen an exponential growth in the number of professional sensors designed to deliver exceptional performance in any environment. The observed increase is related, among others, to the spread of the idea of a smart home and, consequently, the demand for good-quality climate sensors. Among the most used sensors are temperature, humidity, rainfall, road conditions, wind, pressure, and gas concentration sensors.

Usually, the basic criteria determining the application of a given sensor are the range of the detected concentration, the range of operation at appropriate temperatures, the response time, the ability to work in a dedicated environment and the price. For example, for one of the most demanding locations, such as garage halls, for carbon monoxide and nitrogen dioxide sensors, the minimum resolution should be up to 1ppm for a carbon monoxide sensor and 0.1 ppm for nitrogen dioxide. Two Carbon monoxide sensors - SPEC-ULPSM-CO [50] and Nitrogen dioxide SPEC-ULPSM-NO2-V2 [51] were used in the tests. These sensors can work in the temperatures and atmospheric conditions of industrial buildings (0 - 50 ˚C, 5 – 95 % RH - for the carbon monoxide sensor and -20 ˚C – 40 ˚C, 15 – 95 % RH - for the nitrogen dioxide sensor). Their measuring range is 0-800 ppm for a carbon monoxide sensor and 0-20 ppm for a nitrogen dioxide sensor. The response time is acceptable and is less than 60 seconds for the carbon monoxide sensor and less than 30 seconds for the nitrogen dioxide sensor, respectively. There is no need for high accuracy with a carbon dioxide sensor. There are sensors in the NIDR technology on the market with an appropriate accuracy of ± 50 ppm. An exemplary sensor provides (FIGARO CDM7160-C00 [52]) an appropriate measurement range of 300-5,000 ppm, with an acceptable temperature and humidity range of 0-50 ˚C, 0-85% RH. Response time less than 120 s. In the case of measuring the concentration of propane-butane, the satisfactory measuring range is from 0 to 1900 ppm. One of the suggestions may be sensor - FIGARO LPM2610 [53]. One of the most popular sensors used to measure temperature and humidity is DHT 11. It is a sensor equipped with a calibrated digital signal output. Its technology ensures high reliability and excellent long-term stability. A high-performance 8-bit microcontroller is embedded in the sensor. DHT 11 includes a resistance element for humidity measurement and an NTC thermistor for temperature measurement. In the case of measuring CO_2 concentration, optical sensors are most often used. The sensors use the phenomenon of light absorption by the gas mixture flowing between the transmitter and receiver (e.g., air with CO_2 content). A wide range of CO_2 sensors on the market allows you to choose the optimal solution for your application. One of the most frequently used sensors is the CO2Engine® K30 -STA sensor manufactured by SenseAir [54]. In addition to the aforementioned parameters, carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NOx) can also be measured [55,56].

Measurement stations are an alternative to single systems. A good example is the Bosch Sensortec family of environmental sensors, which includes barometric pressure sensors, humidity sensors that measure air pressure, ambient temperature, and relative humidity, as well as integrated four-in-one gas sensors [57]. A slightly different approach is presented by the IEI company offering HOBO RX3000 stations, which can be equipped with a number of sensors such as: temperature, relative humidity, wind speed and direction, barometric pressure, solar radiation, rainfall, leaf wetness, photosynthetic light [58,59].

A properly selected location of stations in the metropolitan area provides opportunity to measure conditions of the downtown and city outskirts simultaneously. Later, after all the necessary applications are fully launched, selected system components will be installed in subsequent points. The list of equipment dedicated to a specific place will take into account the diversity of existing threats to the air quality. Access to measurements is possible from any Internet access point.

Nowadays distributed measurement systems of the city-wide scale can be built using the Internet of Things concept [60]. Each end device is an Internet network node even though the network itself is still a complex conglomerate of different technologies: wireless, wired, and optical fiber. The choice of particular standard is crucial for future deployment of the system. There are numerous initiatives which successfully built such networks [61-76].

Wi-Fi that is based on IEEE 802.11 standard still is a very popular wireless method to connect devices to the Internet. Ease of use and wide adoption of Access Points in business and households make it a viable solution that does not burden end users with too sophisticated technological issues [61]. Therefore, many devices advertised as Internet-of-Things equipment follow this path, although there are some drawbacks of this approach. Primarily, communication range is limited up to several dozens of meters. Extending Wi-Fi range with directional antennas is usually against regulations concerning electromagnetic fields. Example of a particulate matter sensor device LookO2 which is connected to the Internet by means of IEEE 802.11 is shown in Figure 3.

Fig.3. Particulate matter measurement IoT device LookO2v3.

Main problem with devices built with focus on Wi-Fi is that they depend on local and private networking infrastructure. As such this technology is not feasible for large scale deployments of sensor networks. Alternatively, one may consider connection via cellular mobile networks such as GSM. In this area for a long time there was limited progress, and the only viable option was slow and expensive General Packet Radio Service (GPRS) available in GSM version 3G. Despite its limitations it enabled successful monitoring systems. Recently GSM rapidly advanced to version 5G that took into consideration requirements of IoT equipment.

Designers of GSM standard became aware that not everyone needs broadband Internet connection and that there are business opportunities in providing slow, cheap but also reliable Internet connection at long distances in cellular fashion. This offspring of GSM is known as Narrowband IoT (NB-IoT) [76]. Despite the fact that NB-IoT has its own, dedicated subchannel within 5G, there are some concerns about interference with GSM technology [34]. Furthermore, it requires the end user to make an agreement with the GSM network provider and pay a regular fee.

There is also a middle ground between these two categories that requires some more engineering effort but comes with significantly longer distance than in the case of Wi-Fi and with smaller operational costs than in case of NB-IoT. This range of techniques is occupied by standards that were designed ground-up for the IoT only. LoRa is an example of such a standard [64]. It works within ISM free-of-charge bands therefore everyone can establish their own LoRa network as there is no central governing body just like in the case of Wi-Fi networks. However, unlike Wi-Fi the LoRa link typically has a range of several kilometers using omnidirectional antennas on both ends. LoRa technology is protected by patents but fees to the patent owner are collected from semiconductor manufacturers thus making this cost invisible to end users who just have to pay for physical chips and communication devices. With this simplified business model comes an inconvenience typical for all ISM bands that is possible clogging of the communication channel due to the large number of networks established in the same area. Most popular chip providing LoRa is SX1276 which is shown in Figure 4 as an embedded component of Raspberry Pi extension board.

Fig. 4. Extension board for Raspberry Pi providing LoRa communication.

Technologies and standards discussed above are just examples of possible options to choose from which are available to IoT network designers [65]. As for long-range data transmission there are other standards dedicated to IoT such as Sigfox, which is characteristic for its enormous communication range reaching hundreds of kilometers. However, it is proprietary technology that is not enrolled globally and available in a limited number of countries. For upper layers of IoT networking systems there are many protocols as well.

In wide area networks two standards dominate:

- Representational State Transfer (REST) built upon HTTP protocol [66],
- Message Queuing Telemetry Transport (MQTT) [57].

Each of them has its own advantages and disadvantages. REST separates clients from servers using a well-known and open HTTP standard that is highly portable and available to all computers from high-end servers to small microcontrollers. It is just as scalable as the HTTP servers are with their replication and virtualization methods that are commonly used nowadays [59]. which make it suitable for numerous end devices that may communicate simultaneously in the IoT. With REST it is possible to transmit any kind of data, but JavaScript Object Notation (JSON) gained popularity due to its simplicity and lightweightness.

MQTT is another lightweight protocol tailored in its early days for transmission of measurement data. This protocol is built upon the TCP/IP stack and uses the idea of a central server on which MQTT broker is available. Clients publish data to the broker and may subscribe to receive that data. In theory an MQTT broker should retransmit data to all subscribers of a particular “topic” with which the message was initially published. However, quite often it works as a simple to use and secure intermediary layer between IoT end devices and the database server. Using these methods, a measurement network for particulate matter measurements can be densely deployed in municipal areas. The purpose of this review was not to compare the accuracy of the sensors used or their reliability. The main objective was to show the main trends occurring in the field of air quality monitoring from the sensors and signal transmission point of view. Due to the very large number of sensors used in both the high and low quality classes, it is neither possible nor advisable to compare their properties. In general, it can be said that there is no problem at all with the selection of suitable sensors and everything depends on the budget available. As shown in the review, when cheaper sensors are used, their performance is improved by advanced signal processing techniques or cyclic calibration. In both cases, the desired results may be obtained. A relatively new approach is the construction of a sensor network consisting of a set of low-cost sensors and a few stations of higher quality activated when alarm thresholds are exceeded. The same goes for wireless communication. The authors of the discussed articles show the possibility of using both cellular telephony as a means of information transmission over unlimited distances and LoRa, Wifi, or *Bluetooth* transmission standards for closer distances. According to the authors' experience, the best solution is to combine both technique, the LoRa standard with 5G cellular telephony. The proliferation of IoT technology is also finding its way into the field of environmental monitoring. It is increasingly common to see systems managed using this technology.

Conclusions

The problem of air quality measurement presented in the article is still relevant and is gaining in importance as civilization develops. From year to year, more and more individual measuring stations and measuring networks are created, monitoring the current weather conditions and warning about excessive concentration of harmful substances and PM.

The overview of the most relevant air contaminants presented in this article allows the necessity of applying appropriate countermeasures to be assessed. The review of the work carried out in the field of air pollution measurement shows that this subject is taken very seriously. Both in the area of sensors and measurement systems one can see significant progress caused, among other things, by the widespread use of advanced signal processing algorithms on the one hand and the use of the latest information technologies on the other hand.

One of the more significant results of the work carried out is the possibility of replacing professional measurement stations with a range of low-cost sensors working in IoT structures. The effects obtained in this way are comparable to those obtained from much more expensive measuring stations.

The main purpose of the article was not to compare different types of sensors or systems in terms of their quality or price. We can find many such studies in the literature, their common feature is that they become outdated very quickly. However, showing the emerging trends gives the best information on the current state of environmental monitoring systems.

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