A PORTABLE AIR QUALITY MONITOR BASED ON LOW-COST SENSORS

by

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National systems of automatic air quality monitoring are based on automatic measuring instruments that are installed in stationary air quality monitoring stations. Substantial financial resources are required for the procurement, installation, calibration, and maintenance of such measuring devices. For this reason, existing national and local air quality monitoring networks are not able to provide a high temporal and spatial resolution of measurement results. In the last decade, as a possible alternative to the conventional approach to air quality monitoring, real-time monitoring systems using low-cost sensors and sensor platforms have begun to be applied. This paper describes the basic characteristics of a portable air quality monitor PAQMAN 2020 based on low-cost sensors. Part of the results of comparative measurements of this device with the reference instruments is presented in the paper.

Key words*: air quality, monitoring, low-cost, particulate matter, CO, sensors*

Introduction

Exposure to air pollution by particulate matter (PM) has been shown to cause cardiovascular disease, asthma, lung cancer, and other respiratory diseases [1-3]. Therefore, the World Health Organization (WHO) has prescribed guidelines on air quality, and the EU Council has prescribed Air Quality Directives and other related documents related to PM concentrations in the air [4]. Conventional air quality monitoring (AQM) systems are based on a limited number of fixed AQM stations with stationary PM analyzers. Such instruments are large in size and expensive to procure and maintain. This situation makes it difficult to monitor PM concentrations in cities, where high spatial and temporal measurement resolution is required in order to provide up-to-date real-time air quality information to citizens. In the last few years, work has been done to improve existing AQM systems in terms of economy

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and efficiency by using low-cost PM sensors and sensor platforms. This technical solution uses low-cost sensors available on the market as sensitive elements.

Gravimetric methods are the basis of European and American reference methods for measuring concentrations of PM_{10} and $PM_{2.5}$ in ambient air. Compared to automatic monitors, gravimetric tracking methods require conditioning and measuring filters, and therefore such methods are time-consuming and expensive. Due to the lengthy gravimetric procedure, the results are available a few days after sampling, while automatic online monitors display the results of PM measurements in real-time [5].

The SEPA started automatic monitoring of air pollution in the Republic of Serbia in 2006. Today, SEPA manages almost 40 automatic AQM stations of about 60 AQM installed in the Republic of Serbia. Most AQM stations (28) were equipped under the project Europe Aid/124394/D/SUP/IU *Supply of Equipment for Air Monitoring* and started operating in 2009 and 2010. According to the data presented on the SEPA website [6], in the Republic of Serbia, about 35 AQM stations are capable to monitor real-time PM mass concentration (PM_{10} and $PM_{2.5}$) using GRIMM EDM 180 monitors, which is a reference-equivalent monitor for PM_{10} [7]. The high cost of these analyzers and the cost of maintaining them are limiting factors for the expansion of national monitoring networks. On the other hand, in order to better assess the impact of air pollution on human health, it is necessary to perform continuous real-time air quality monitoring in micro-environments where people most often live (part of settlements, streets, schools, hospitals, factories, housing, *etc.*) [8]. The spatial coverage of the Republic of Serbia with AQM stations and stationary automatic PM monitors is uneven because most automatic PM monitors are concentrated in the area of city of Belgrade (more than 20 of totally 35). Therefore, there is a real need for instruments for measuring PM particle concentrations that are reliable enough to assess the impact of suspended particles on human health based on the measurement results, *i.e.* to avoid the risk of exposing the population to high PM concentrations. These instruments should provide information about the PM mass concentrations in real-time. So it comes to that suitable tools to quantify PM concentrations need to be developed. On account of these, the researchers have started developing systems with easily available sensors, which have low prices and quick response time.

Portable PM monitoring devices

In addition to stationary PM monitors, commercially available portable devices are used to monitor PM concentrations in the world, which mainly work on the optical principle (particle counting and conversion of that number into mass concentrations). The dimensions of portable PM monitors are much smaller compared to stationary PM monitors, and their prices range from a few hundred to several thousand euro's (stationary PM monitors cost up to 20000 €).

Commercially available portable PM monitoring devices usually work on the light scattering principle. These devices, in fact, calculate the mass concentration based on the intensity of light scattered from particles. The optical scattering efficiency per unit mass is not constant with respect to the particulate size and composition. Therefore, these instruments deliver an accurate PM mass concentration only if particle size distribution and composition are not very different from the calibration standard. Biases in PM exposure estimates may also be due to an incomplete capture of the particle size ranges [9]. Moreover, PM mass concentrations measured with any light scattering instrument increase with the relative humidity due to an increase of the average particle size associated with the condensational growth of its hygroscopic components [5, 10, 11].

Figure 1. Portable PM monitors: (a) Turnkey Instruments OSIRIS, (b) TSI DUSTTRAK 8533, and (c) Dylos Corporation Dylos 1700

The OSIRIS (Turnkey Instruments), shown in fig. 1(a), have been used for the assessment of indoor and outdoor PM levels as well as personal exposure in a number of studies [5, 12]. This monitor is designed for the measurement of PM (PM_{10}, $PM_{2.5}$, and PM_1) mass concentrations in the range of 0.5-20 μm [5]. The portable aerosol monitor DustTrak Model 8533 (TSI), shown in fig. 1(b), is also widely used to monitor PM mass concentrations in indoor and outdoor environments [5]. This is a real-time, small, and portable monitor that uses orthogonal light scattering (reflected light) technology. The Dylos air quality monitor (Dylos Corporation), shown in fig. 1(c), is widely used in homes and offices to monitor PM number concentrations [9]. The Dylos reports particle numbers in two size fractions: $PM_{0.5}$ which measures particles sized 0.5 μm and greater, and $PM_{2.5}$ which measures particles sized 2.5 μm and greater. The comparability between such portable PM_{10} monitors and instruments that are equivalent to reference measurement method has been tested also [5]. Additional information about personal and ambient measurements of PM should be found in the references [13, 14].

Low-cost PM sensors and monitors

In the last decade, air quality monitoring devices that use low-cost gas and PM sensors have been available on the market. Devices that consist of a number of low-cost sensors, microcontrollers, communication modules, and power modules are called sensor platforms. The PM sensors and sensor platforms have low power consumption and require almost no maintenance during operation. Also, they are smaller in size and significantly cheaper than stationary PM monitors used in the national AQM networks, so they can be more easily procured and installed.

However, before the implementation of low-cost sensors, it is necessary to ensure the reproducibility of sensor and platform measurements through compliance with all QA/QC procedures as in the case of national monitoring networks. Therefore, it is necessary to calibrate the sensor in controlled laboratory conditions and in the field, determine the measurement errors of sensors and platforms, examine the influence of meteorological factors on measurement errors and the like. The European Committee for Standardization (CEN/TC264/WG42) is still working on defining technical specifications and conditions under which low-cost sensors should be tested in laboratory and field conditions [15].

Also, low-cost PM sensors are sensitive to changes in T and RH air, as well as exposure to wind and sun. All these facts clearly indicate the problem of ensuring the quality of data obtained using low-cost sensors and platforms, which are prescribed by the Air Quality Directive [4]. This Directive prescribes a Data Quality Objective (DQO) target for indicative measurements. DQO is a measure of acceptable uncertainty that monitoring methods need to meet when indicative measurements are concerned. According to the Directive, the permissible measurement uncertainties are 50% for PM_{10} and $PM_{2.5}$, 30% for O_3, and 25% for CO, NO_x, NO_2, and SO_2.

Low-cost CO_2 sensors and monitors

The value of CO_2 concentrations in outdoor air is typically in the range of 350 to 400 ppm, and if there are significant industrial facilities in the vicinity or a high level of traffic, these values can be even higher. The main source of CO_2 in rooms (classrooms, offices) is breathing, and the level of CO_2 concentration depends on the number of people, the period of stay in the room, the amount of fresh air entering the room, the size of the room and the concentration of CO_2 in the outside air. Input parameters of the internal environment for the design and assessment of energy performance of buildings, indoor air quality, thermal environment, lighting, and acoustics are defined on the basis of European standard EN15251 [16], which was adopted in the Republic of Serbia. In this standard, indoor air quality is categorized based on the differences between indoor and outdoor CO_2 concentration. Four air quality categories are defined, with Category II recommended for school buildings.

The goal of CO_2 monitoring is to ensure good indoor air quality (business premises, offices, classrooms, living spaces). The non-dispersive infrared (NDIR) sensor is the most commonly used type of CO_2 sensor for industrial measurements. A typical NDIR CO_2 sensor consists of a chamber with an infrared (IR) light source at one end and a detector at the other end. The IR light is directed through a sensor chamber through which gas passes. In front of the IR detector is a filter that eliminates all IR light except the one with a wavelength of 4.26 μm that only CO_2 molecules can absorb. The CO_2 concentration is determined by measuring the intensity of the light reaching the detector.

Portable air quality monitoring and acquisition node 2020 (PAQMAN 2020)

Due to the growing need for air quality monitoring, both in ambient and indoor air, in the Mining and Metallurgy Institute Bor, and Institute Vinča, University of Belgrade, Republic of Serbia, in the previous years' lot of work was done on the development and implementation of a new, low-cost air quality monitor. As part of the research conducted within the national projects, the air quality monitor named PAQMAN 2020 was realized.

Figure 2. The external appearance of the PAQMAN 2020

General characteristics of the PAQMAN 2020

The realized air quality monitor PAQMAN 2020 is primarily intended for indicative measurements of PM mass concentrations in the air, fractions PM_{10} and $PM_{2.5}$, from the range of 0-1000 $\mu g/m^3$, as well as for measurements of temperature (from –10 °C to +40 °C) and relative humidity (RH) of ambient air (from 20 to 90% RH). However, there is a possibility for the installation of additional sensor modules into the device.

The addition of modules for measuring mass concentrations of CO_2, volatile organic compounds (VOC – formaldehyde), and atmospheric pressure is possible at the moment. With the addition of the NDIR S8 CO_2 module [17] the device can be used for indicative measurements of CO_2 mass concentrations in the air in the concentration range from 400 ppm to 2000 ppm. With the addition of the VOC module [18] the device can be used for indicative measurement of formaldehyde concentrations in the range from 0 ppm to 70 ppm. With the addition of the BMP180 sensor module [19], the device can be used to measure atmospheric pressure in the range of 300 hPa to 1100 hPa. The external appearance of the device is shown in fig. 2. The PAQMAN 2020 is housed in a plastic box with dimensions 250 × 160 × 90 mm. The weight of the device is 800 g. The device consists of list of modules connected to microcontroller board as listed below. All device modules, except the keyboard and display, are attached to the bottom of the housing using a plastic support plate with dimensions 220 × 140 × 2 mm. The keyboard and display are attached to the housing cover.

Power supply module

The device is powered by +12 V DC, via a DC connector on the side of the housing. The required power is up to 6 W (12V DC, 400-500 mA that depends on the number of connected sensor modules). The device contains an internal power supply module (block diagram shown in fig. 3) that uses 3 Li-ion batteries (3.7 V, 6800 mAh) which allows four hours of autonomous operation.

Microcontroller board

The Arduino Mega [20] is a microcontroller board based on the ATmega2560 (8-bit) microcontroller. The board has 54 digital I/O ports (14 of which can be used as PWM outputs), 16 analog inputs, 4 UART (hardware serial ports), 16 MHz crystal oscillator, USB port, power port, ICSP connector and reset key. It can be powered by AC/DC adapter (7-12 V DC) or from the computer via a USB connector (5 V DC). All PAQMON 2020 modules are connected to the Arduino Mega microcontroller board, either directly or using an additional Arduino microcontroller board (if needed).

The PM sensor module

The PM sensor module SDS011 [21] uses an optical method (light scattering from particles passing through the detector) to determine the concentration of PM particles in the air, fractions PM_{10} and $PM_{2.5}$, from the range 0-1000 $\mu g/m^3$. This PM module can be used to measure the mass concentrations of PM particles with a diameter in the range of 0.3 µm to 10 µm. The laser diode built into the PM sensor is of high quality so that the lifespan of the light source is up to 8000 hours. The typical reading of the sensor for zero input value is from 0.1 $\mu g/m^3$ to 0.4 $\mu g/m^3$ for both PM fractions. After prolonged use, *e.g.*, after several months of measurement, this value can increase to around 1.0 $\mu g/m^3$, which is an indication that the sensor needs to be cleaned.

The CO_2 sensor module - SenseAir S8

The SenseAir S8 sensor module [17] is intended for measurements of CO_2 concentration in the air in the range from 400 ppm to 2000 ppm. This module uses NDIR operating principle. The module has a built-in serial port (UART).

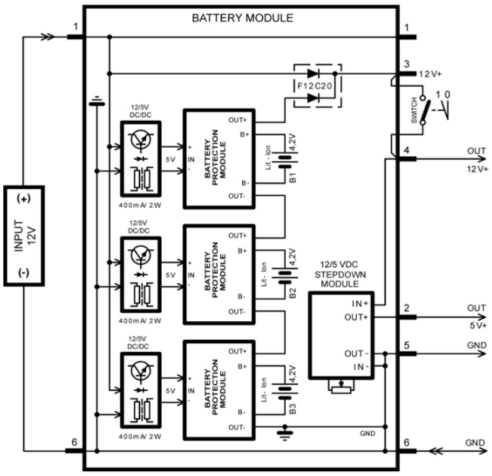

Figure 3. Block diagram of the power supply module of the PAQMAN 2020 device

MicroSD card module with PI interface

The MicroSD Card Adapter module [22] allows reading and writing data to files on the SD card, using the SPI interface. The module required a DC voltage of 4.5 V to 5.5 V.

The DS3231 real time clock module (RTC Module)

The RTC module provides real-time information (seconds, minutes, hours, day, date, month, and year). The DS3231 is an inexpensive, highly accurate temperature-compensated real-time clock (RTC) with an integrated crystal oscillator [23]. The I^2C bus is used to transfer data between the RTC module and the microcontroller. A 3.6 V LIR2032 lithium-ion rechargeable battery installed in the RTC module enables continuous work of this module over a long time period (several years).

Module for T and RH measurements (DHT22 module)

The DHT22 (another name is AM2302) digital module is used for the temperature and relative humidity measurements [24]. Power supply voltage for this module should be 3.3-6 V DC. The sensing elements are connected to an 8-bit microcontroller built into the module.

The LCD module (LCD2004)

The LCD2004 is an LCD module that allows the display of 20 × 4 characters and has an I^2C interface [25]. The I^2C bus uses two two-way signal lines, a serial data line (SDA) and a serial clock line (SCL). Supply voltage: 5 V DC.

Matrix keyboard with 16 keys

For human interaction with the PAQMAN-2020, a matrix keyboard with 16 keys is used, with dimensions: 69x76x8 mm. The keyboard is attached to the device's front cover.

The VOC sensor

The MS1100 sensor [18] is intended for measuring volatile organic compounds. This sensor can be used to determine the concentrations of formaldehyde (toluene) and toluene (toluene) in the air. At the moment, only subroutine for the determination of the formaldehyde concentrations in the range from 0 ppm to 70 ppm has been implemented in the PAQMAN 2020 software.

Air pressure measuring module - BMP180

The BMP180 air pressure module [19] is factory calibrated. Data exchange with Arduino Mega microcontroller is done via an I^2C bus. Module characteristics: Supply voltage from 1.8 to 3.6 V DC. Power consumption: 0.5 μA at a reading frequency of 1 Hz.

Connecting the PAQMAN 2020 modules

The block diagram of the power supply module of the PAQMAN 2020 device is shown in fig. 3. An input voltage of 12 V DC is applied to the power supply module. This module controls the charging and discharging of each Li-ion battery. If the switch, (shown in fig. 3), is in Position 1, all device modules are powered from the power supply module. The 12 V DC voltage is transmitted directly to the power inputs of the Arduino microcontrollers. For the operation of other modules, the required voltage of 5 V DC is obtained via a step-down circuit 12 V/5 V DC. The PAQMAN 2020 connection diagram is shown in fig. 4.

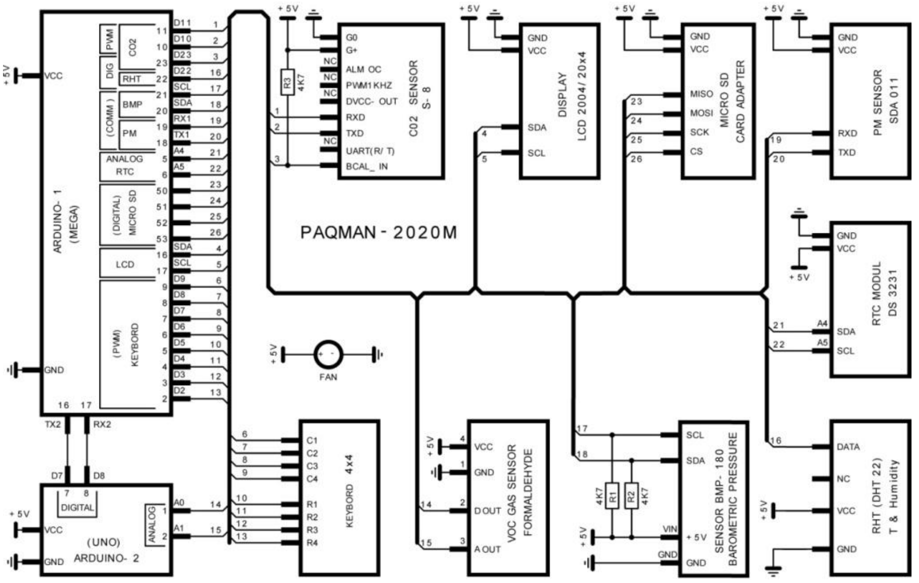

Figure 4. The PAQMAN 2020 connection diagram

The PAQMAN 2020 software

The programming of Arduino microcontrollers built into the PAQMAN 2020 was done using the Arduino IDE (Integrated Development Environment) [26]. The main reason for choosing the Arduino development platform is the fact that programming microcontrollers within this platform is simple and requires only a USB cable and a PC. In addition, the Arduino programming language is a simplified version of the C++ programming language, which further simplifies microcontroller programming. Also, a large number of examples and libraries can be found on the Internet that facilitates the writing of complex programs and the interaction of the Arduino platform with various hardware devices.

The predefined sampling interval is set to one second while the averaging interval is set to 1 minute. If needed, the averaging interval could be set up in the range from 5 seconds up to 1 hours. The results of measurements can be simply downloaded to a PC over a standard USB serial port. The typical capacity of the memory of an SD card integrated into a device is 32 GB, which allows several months of continuous operation without clearing the memory.

The program installed in the PAQMAN 2020 executes the sequence of commands, as follows:

- Checking if any of the keys on the keyboard are pressed. Activating the corresponding key on the keyboard starts the execution of one of the subprograms. In this way, one can choose the interval for averaging the measurement results, delete the results stored on the SD card, set the date and time, set the PM correction factor, send the measurement results to the serial port, and so on.
- Reading the data from the connected modules, their logical control, and averaging.
- Writing measurement results into the files on the SD card module and on the LCD display.
- Reading the measurement results from the file on the SD card module and sending them to the serial port (if needed, upon the demand from the keyboard).

Testing the characteristics of the PAQMAN 2020

Examination of the characteristics of the realized device included monitoring the stability in operation, as well as comparing the measurement results of this instrument with other reference measuring instruments. Tests of the device characteristics were performed both in laboratory conditions and in the field. The device has been tested in continuous operation for more than 1 year, of which 2/3 of days in laboratory conditions and about 1/3 days in the field. In that period, comparative measurements of PM_{10}, $PM_{2.5}$, CO_2, T, RH, and P were performed with reference instruments or instruments that use equivalent measurement methods in relation to reference methods.

Testing the characteristics of the PAQMAN 2020 in laboratory conditions

The device was tested in the laboratory for applied electronics and computer engineering at the Institute of Mining and Metallurgy Bor. In this laboratory, comparative measurements of PM_{10}, $PM_{2.5}$, CO_2, T, RH, and P were performed with the PAQMAN 2020 device and commercially available calibrated instruments for the stated parameters. The WS500-UMB Smart Weather Sensor was used as a reference instrument (ref) for measuring temperature, relative humidity, and air pressure [27]. As a reference instrument (ref) for measuring PM_{10} and $PM_{2.5}$ concentrations in the laboratory and comparing with the measurement results of NOVA SDS 011 sensors device under test (DUT), an automatic PM Turnkey Osiris monitor was used, which was previously calibrated using the gravimetric method, in the manner described in [5]. In order to calibrate PM sensors integrated into the PAQMAN 2020 devices the PM concentration values obtained by PAQMAN 2020 were corrected following the slightly modified method proposed in the reference [5]. The PM results of PAQMAN 2020 were scaled using a specific correction factor as shown in:

$$F = \frac{1}{n}\sum_{i=1}^{n}\frac{\mathrm{O}_i}{\mathrm{P}_i} \tag{1}$$

where F is the correction factor, n is the number of days, O_i is the 24-hour mean PM concentration for i^{th} day of measurements obtained by Turnkey OSIRIS monitor, and P_i is the corresponding 24 hour mean PM concentration obtained by PAQMAN 2020 for the i^{th} day of measurements. Each 1 minute PM result obtained by the PAQMAN 2020 was multiplied by this correction factor.

Some results of the comparative measurements of PM concentrations are shown in fig. 5. The 15 minute or 1 hour mean values were compared, depending on the available time resolution of the measurements from the reference instruments. Figure 5 shows a comparative representation of the concentrations of PM_{10} and $PM_{2.5}$ in the form of XY diagrams. Determination coefficients (R^2 = 0.957 for PM_{10}, and R^2 = 0.945 for $PM_{2.5}$) indicate a very strong linear relationship between the measurement results of the reference instrument and the NOVA SDS 011 sensor. After applying the correction factor, the uncertainty for PM_{10} measurements obtained in the laboratory was 13%, while the uncertainty for $PM_{2.5}$ measurements was 18%.

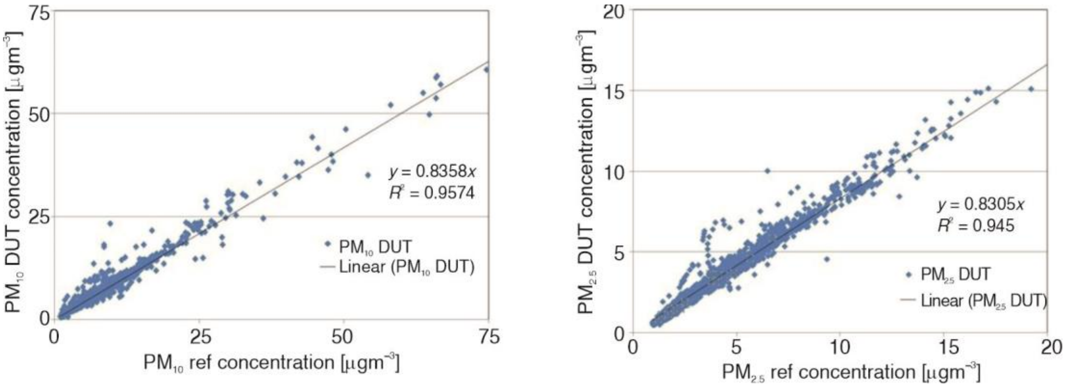

Figure 5. Comparison of PM results in the laboratory: ref (Turnkey Osiris) *vs*. NOVA SDS011 (DUT)

Based on the comparison of the measurement results of the CO_2 sensor and the reference device, shown in the reference [28], it can be concluded that the characteristics of the tested SenseAir S8 sensor integrated in PAQMAN 2020 meet the criteria required for indicative measurements of CO_2 concentrations in indoor air.

Tests of sensors for T, RH, and atmospheric pressure in laboratory conditions also showed that in relation to the reference instruments the values of R^2 are above 0.95, which indicates a very good agreement between the measurement results.

Testing the characteristics of the PAQMAN 2020 in the field

Despite the fact that the PAQMAN 2020 is primarily intended for indoor use, it has also been tested in the field, using a housing that protects it from atmospheric precipitation. The device is located near the SEPA automatic air quality monitoring station (AAQMS) Town Park in Bor (44° 04' 33" N, 22° 05' 58" E) [6]. Comparative measurements of PM with Grimm EDM180 PM monitoring system that provides 1 hour average PM mass concentrations were performed for 20 days (10 days in the heating season and 10 days in the non-

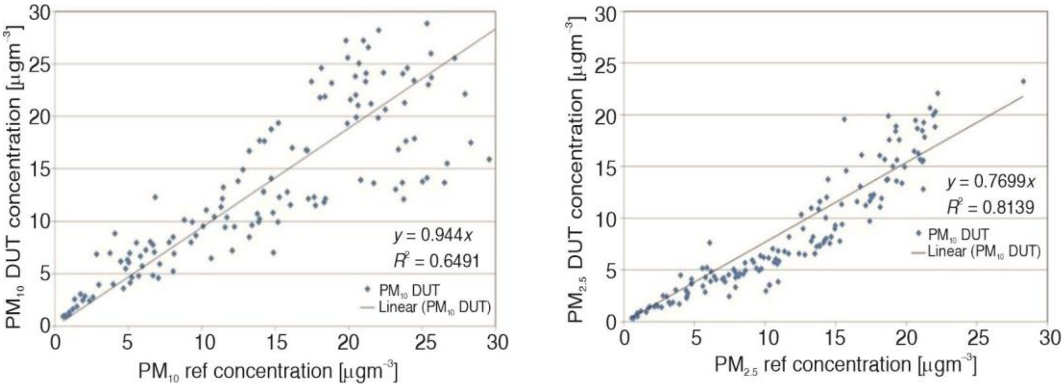

Figure 6. Comparison of PM results in the field: ref (Grimm EDM180) *vs*. NOVA SDS011 (DUT)

heating season). Some results of the comparative measurements of PM concentrations are shown in fig. 6. Determination coefficients (R2 = 0.649 for PM10, and R2 = 0.811 for PM2.5) indicate a moderate and strong linear dependence of the measurement results of the reference instrument and sensor NOVA SDS 011, despite the fact that the measurement campaign was conducted in the winter. After applying the correction factor, the uncertainty for PM10 measurements obtained in the field was 16%, while the uncertainty for PM2.5 measurements was 24%. During the campaign, the largest percentage of days was with precipitation. The average RH during the measurement campaign was 73%, and the average daily temperature was 2.9 °C.

Conclusions

In the last ten years, low-cost sensors and low-cost monitoring systems have been applied as an alternative to the conventional approach to air quality monitoring. This paper describes the basic components and characteristics of a portable air quality monitor PAQMAN 2020 based on low-cost sensors. In the last three years, we have tested and implemented in different types of PM monitoring devices more than 40 NOVA SDS011 PM sensors. Our experience with NOVA SDS 011 PM sensor is positive, concerning the sensors readings in the indoor air. Not many investigations have been conducted so far in the outdoor air. There were just a few malfunctions of the sensors fan that use to be quite loud so it needed replacement. The lowest values of R^2 between the PM sensor and reference instruments were obtained in outdoor air while the highest values were obtained in indoor air with R^2 values higher than 0.93 (30% < RH < 70%). High RH values (over 70%) negatively affected the PM monitor's response, especially in the case of PM_{10} concentrations (high overestimation). Tests of sensors for T, RH, and atmospheric pressure in laboratory conditions also showed that in relation to the reference instruments the values of R^2 are above 0.95, which indicates a very good agreement between the measurement results. It was determined that after applying the correction factor to the PM results, as shown in this paper, PAQMAN 2020 satisfies data quality objectives for indicative ambient air quality assessment regarding the uncertainties for PM measurements. Tests of this monitor will be continued in the outdoor air to find the best model for correcting the influence of humidity, temperature, and other meteorological parameters on the measurement results.

Acknowledgment

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