Metrological features of a beta absorption particulate air monitor operating with wireless communication system

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Abstract. A system for measurements of particulate matter in the ambient air, employing beta absorption instrument AMIZ-2007 with wireless communication facilities based on GPRS technology, is presented. Uncertainty of measurements caused by the counting statistics was analyzed and it was found that at least 3 h of sampling time is needed to achieve coefficient of variation lower than 20% for the average concentration of particulate matter in the ambient air exceeding 10 μg/m³. Application of a C-14 beta ray source instead of Pm-147 improves sensitivity of the measurement ca. two times. Some results of on-line operation of the system with PM10 and PM2.5 samplers are also shown.

Key words: ambient air • beta-ray absorption • particulate matter • wireless communication

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Introduction

Metrological features of a beta absorption particulate air monitor [2] were already considered in the past by some authors [4, 8]. However, recent instruments are totally different from those produced in the past. Implementation of new informatics and communication technologies caused that the modern instruments for particulate monitoring are fully automated and wirelessly controlled devices, operating in large networks, and the results of measurements are instantly presented on the web sites [3, 5, 6]. Moreover, new requirements from the end users appeared. It is expected now that these instruments have to be capable of measuring not only the overall dust suspended in the ambient air, but also its fractions of grain size (aerodynamic diameter) below 10 μm (with PM 10 sampling head [7]) or even 2.5 μm (with PM2.5 probe). Thus, more detailed analysis of the factors influencing uncertainty of the measurement, especially at low concentration of the particulate matter in the air, seems to be necessary.

In this paper, a system for the measurement of particulate matter in the ambient air, employing beta absorption instrument AMIZ-2007 with wireless communication facilities based on GPRS technology, is presented. Also analysis of the measurement uncertainty is carried out and examples of the application of the whole system are shown.

Airborne dust monitoring system AMIZ-2007

An AMIZ-2007 system is designed for automatic measurements of airborne dust concentration in the ambient air. It is also equipped with meteorological sensors measuring temperature, atmospheric pressure and relative humidity of the ambient air. Optionally, the monitor can be fitted with wind speed and wind direction sensors. The principle of the operation is based on the measurements of mass of dust deposited on a fiber glass filter tape, from the known volume of the air. The air volume is determined by pumping period (sampling time), while the air flow is kept constant. The mass of the collected dust is measured basing on absorption of beta rays. Operation of the instrument is controlled by a microprocessor system, which apart from the controlling measuring cycle, processes measured signal, computes dust concentrations and stores the results in a local memory. A block diagram of the AMIZ-2007 monitor is shown in Fig. 1.

In case the AMIZ-2007 operates as an independent individual unit (not in monitoring network), then it is programmed with a local keyboard, and the stored results can be transmitted to an external computer through a USB port. In case the instrument operates in a monitoring network, then the transmission of results and the remote communication with an external computer is realized in a wireless manner by means of the mobile phone network GSM and the internet.

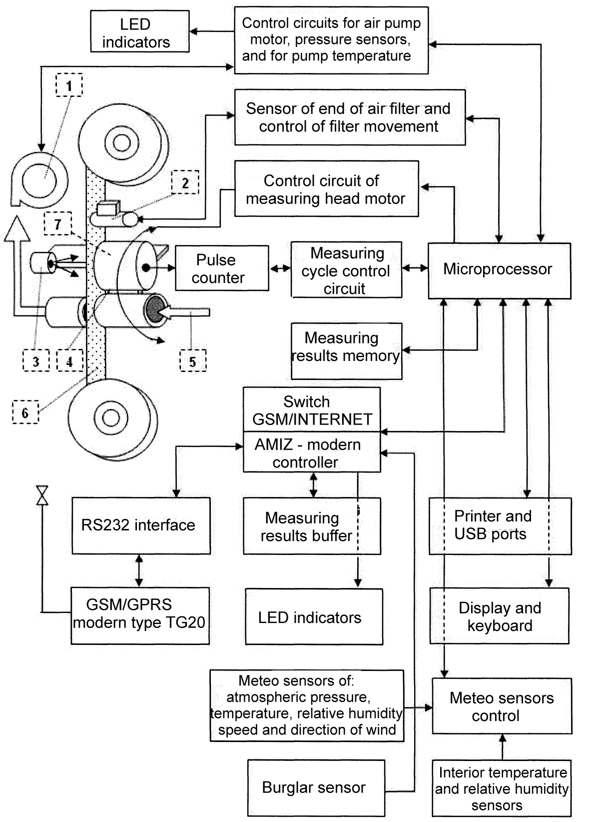

Fig. 1. Block diagram of AMIZ-2007 system. 1 – air pump with temperature sensor; 2 – motor for filter movement; 3 – beta-ray source; 4 – measuring head; 5 – air inlet; 6 – air filter tape; 7 – GM beta-ray detector.

Calibration models

The principle of operation of the radiometric particulate monitors is based on the measurements of the mass per area of the dust collected on the filter band using the absorption of beta rays. Since the mass per area of the clean filter is not homogeneous and varies ca. from 6.5 to 8 mg/cm^2, it is necessary to perform two measurements of the count numbers, one for the clean filter (N_0) and the second for the filter with the collected dust (N_1). The mass per area of the collected dust may be found from the formula (1):

$$m = \frac{1}{k} \ln \frac{N_0}{N_1} \quad (1)$$

where k is a coefficient, whose numeric value for the logarithmic model (1) may be close to beta-ray absorption coefficient [2]. However, due to the fact, that mass of the collected dust is much smaller than the mass of a clean filter, it may be assumed that the difference between the measured count number $N_0 - N_1$ can also be proportional to m, so the linear calibration model can be proposed:

$$m = \frac{1}{k_1}(N_0 - N_1) \quad (2)$$

where k_1 is a proportionality coefficient.

Relation between the filter mass m and the measured differences in the collected count number $N_0 - N_1$ for the linear model (2) and for two radioisotope sources Pm-147 and C-14 is shown in Fig. 2. Correlation coefficient R was about 99.86% for the linear and 99.70% for logarithmic model, so it can be assumed that the metrological features of both the models are almost the same.

The results presented in Fig. 2 show that sensitivity of the measurement, represented by the value of the coefficient k_l, is about two times better for beta rays from C-14 than from the Pm-147 radioactive source. Generally, mass of the deposited particulate matter is within 100 to 300 μg/cm^2.

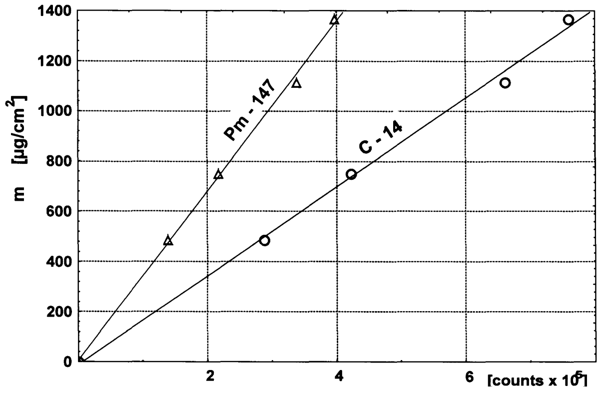

Fig. 2. Relation between the mass per area deposited on the filter vs. number of accumulated count difference for two beta-ray sources C-14 (E_β = 156 keV) and Pm-147 (E_β = 224 keV).

Uncertainty of measurements

The mass per area of the dust m deposited on the filter can be expressed as:

$$m = \frac{Z_{av}Tq}{s} \tag{3}$$

where: $Z_{av} = 1/T \int_0^T z(t)dt$

mean value of the dust concentration in air [μg/m^3] over the sampling period T [h]; $z(t)$ – instant value of the dust concentration; q – air flow rate [m^3/h]; s – active surface area of the filter [cm^2].

Coefficient of variation of the mass per area of the deposited on the filter σ_m/m for the linear and logarithmic models are, respectively to equal:

$$\frac{\sigma_m}{m} = \frac{\sigma_{(N_0-N_1)}}{Z_{av}Tq} \cdot s \tag{4}$$

$$\frac{\sigma_m}{m} = \frac{\sigma_{\ln(N_0/N_1)}}{Z_{av}Tq} \cdot s \tag{5}$$

where: $\sigma^2_{(N0-N1)}$ – variance of the count difference; $\sigma^2_{\ln(N0/N1)}$ – variance of the logarithm of count ratio.

Since the mass of deposited dust is proportional to the measured dust concentration, its variation coefficient, which can be considered as a measure of relative uncertainty $w = (\sigma_{Z_{av}}/Z_{av}) = \sigma_m/m$, can be easily computed for both the models:

$$w_{lin} = \frac{\sqrt{N_0 + N_1}}{k_l Z_{av}Tq} \cdot s \tag{6}$$

$$w_{\log} = \frac{\sqrt{\dfrac{\exp(km)}{N_1}}}{kZ_{av}Tq} \cdot s \tag{7}$$

Relative uncertainty $w_{\log}$ for the logarithmic model was computed using an approximate formula for variance of the count ratio derived in [3].

Having numerical values of the instrument parameters, one can compute the value of relative uncertainty w as a function of sampling time T and for various concentration of the particulate matter in air Z_{av} (Fig. 3). The computations were performed for one particular instrument fitted with the samplers PM10 or PM2.5 and the C-14 or Pm-147 radioactive sources. The flow rate q was 1 m^3/h and the active measurement area about 1 cm^2. It appeared that the computed value w does not depend on the applied calibration model; almost the same value was obtained for the logarithmic as well as linear model. However, the counting uncertainty w is strongly influenced by the energy of used beta radiation. For the C-14 source, emitting beta rays of maximal energy 156 keV, (halving mass $m_{1/2}$ = 2.7 mg/cm^2) [7] the uncertainty is almost two times lower than that for beta rays from Pm-147 of maximal energy 224 keV and halving mass $m_{1/2}$ = 4.5 mg/cm^2. Taking also into account that the radioactive half-life for Pm-147 is 2.6 y, whereas for C-14 it is 5730 y, the superiority of C-14 over Pm-147 is evident.

The chart of uncertainty computed individually for every manufactured gauge can help the end users of the beta absorption particulate monitors in proper setting instrument parameters. It should be mentioned that the considered here uncertainty of measurements pertains only counting statistics and other factors influencing its value were not taken into account in computations.

To examine repeatability of the AMIZ-2007, two instruments were installed in the same place and par-

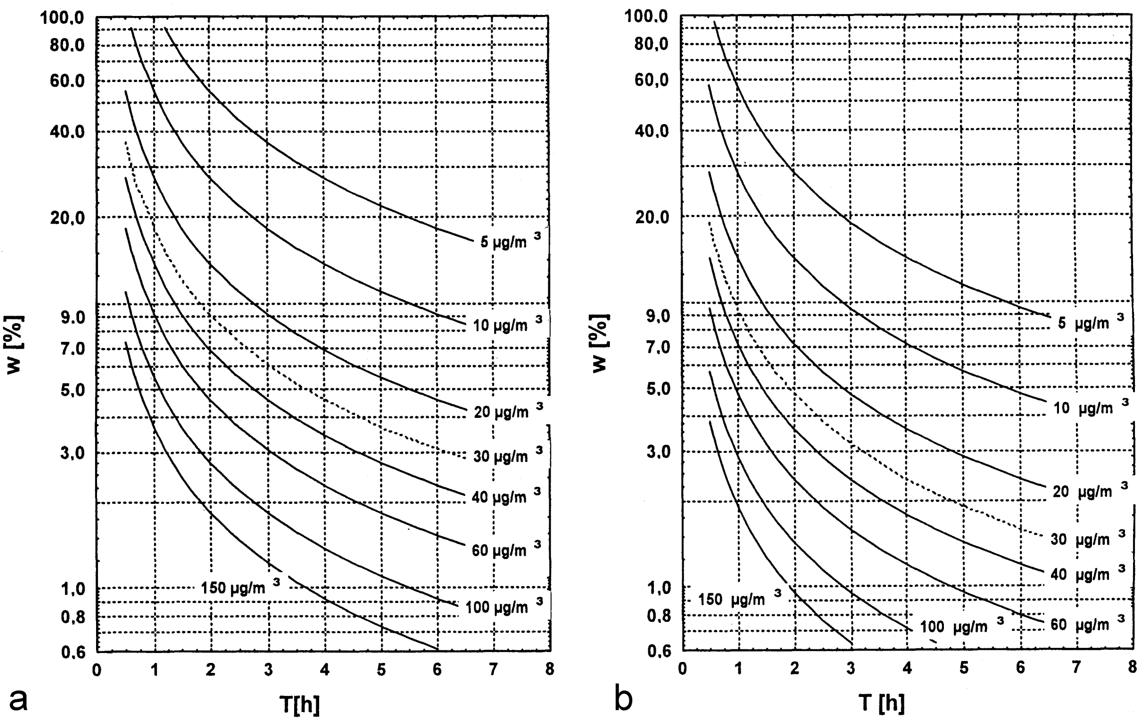

Fig. 3. Calculated relation between the relative uncertainty of measurement (coefficient of variation) vs. sampling time T for various average concentrations of the particulate matter, (a) with Pm-147, (b) with C-14.

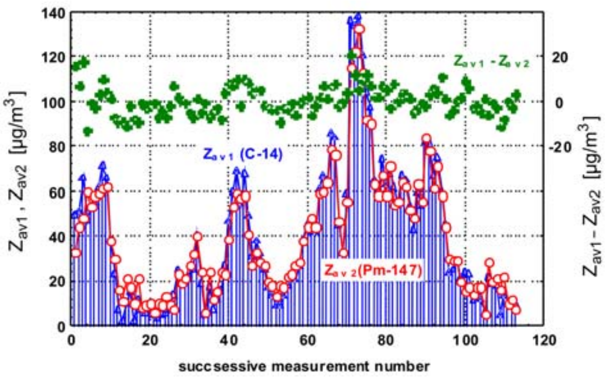

Fig. 4. Particulate matter concentration Z_{av} measured with two separate instruments fitted with PM10 samplers and two different beta-ray sources: C-14 and Pm-147 (1–14 March 2008, to the north of Warsaw).

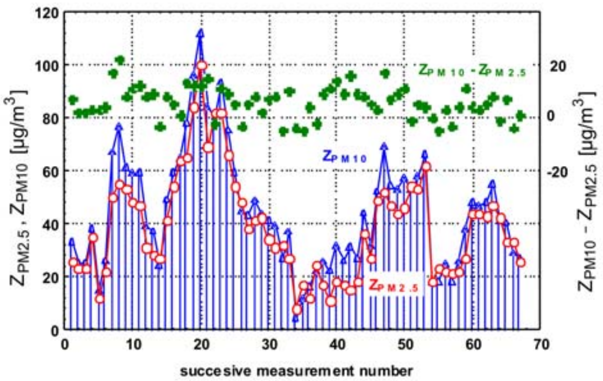

Fig. 5. Particulate matter concentration measured with two separate instruments fitted with PM10 and PM2.5 samplers and with the same beta-ray source Pm-147 (19–27 February 2008, to the north of Warsaw).

allel measurements were carried out. Obtained results of mean concentrations of the particulate matter (Z_{av1}, Z_{av2}) measured with both the instruments in Warsaw, and the difference between them ($Z_{av1} - Z_{av2}$) are plotted in Fig. 4. It can be seen that the mean difference is about 0.4 μg/m³ which is very close to zero and the standard deviation of differences is about 6 μg/m³. This means, that 90% of results obtained in the above experiment differs less than ± 12 μg/m³.

The sampling time was 3 h and was chosen taking into account expected uncertainty of measurements (Fig. 3).

Similar results were obtained for the PM2.5 sampler.

A similar test was carried out for the two instruments with the same beta-ray source, but with the two different samplers: PM2.5 and PM10. Results of that test for 67 successive measurements for a sampling time of 3 h are shown in Fig. 5. Generally, the results obtained using the PM10 sampler are higher than those with PM2.5, but in a few cases lower values are observed. It seems that such an effect can be explained by the relatively high uncertainty of measurements at low concentration of the particulate matter. In the considered test, the mean value of differences between results obtained for both the samplers was about 5.8 μg/m³ and the standard deviation about 6 μg/m³.

Operation in monitoring network

The network operates under control of software installed on the main computer of the monitoring center. Data transmission and communication with the measuring station is carried out in the two configurations:

- Communication network uses only the GSM system,
- Communication network uses both – the GSM and internet system (Fig. 6).

In the first configuration, all information is wirelessly transmitted only to the main computer, whereas in the second the direct communication with the internet is also provided. In this case, all facilities offered by the internet can be employed. The results obtained from

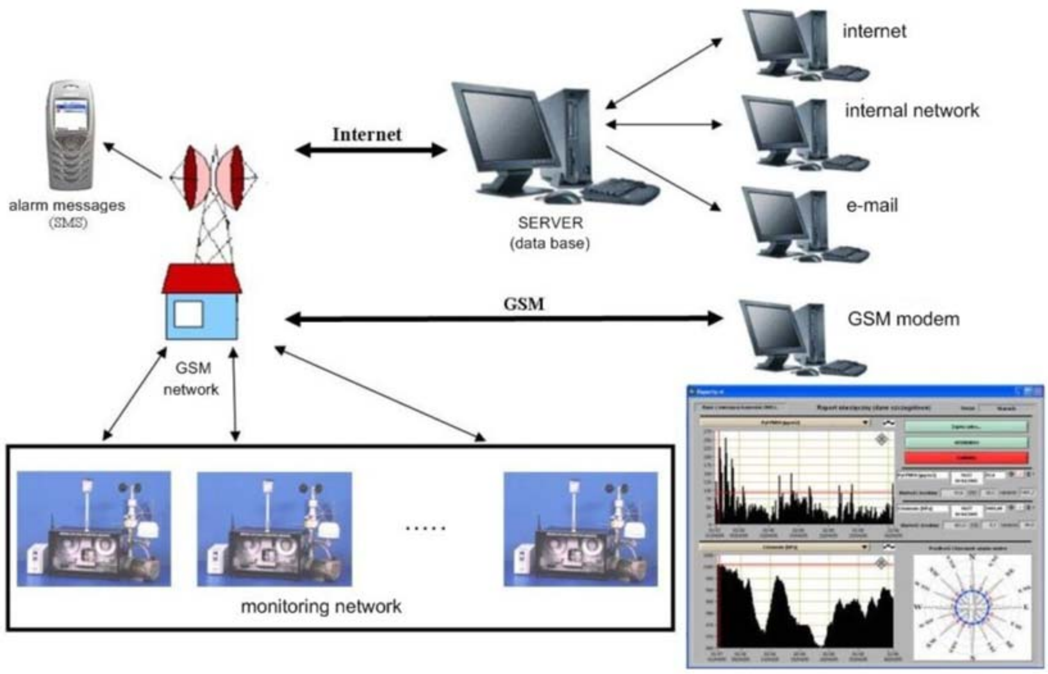

Fig. 6. Diagram of the wireless communication network.

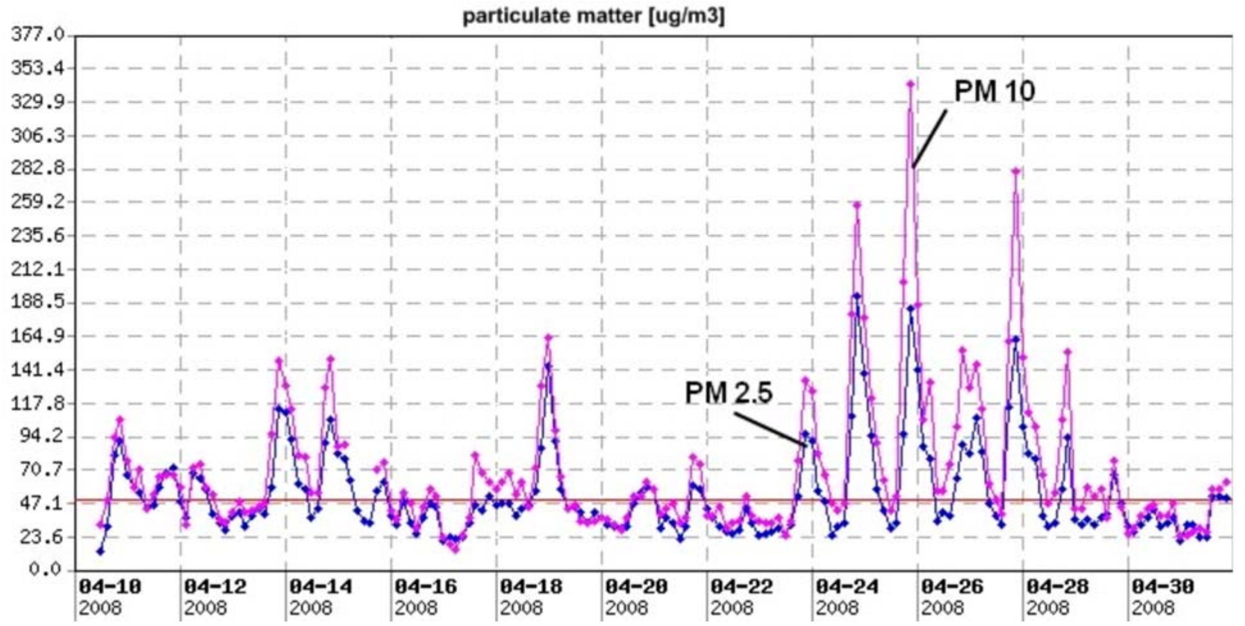

Fig. 7. Results of medium term measurements of the particulate matter with two separate instruments fitted with different samplers PM10 and PM2.5. Sampling time – 3 h. The horizontal line shows the permissible level (50 μg/m^3) of daily average particulate matter concentration.

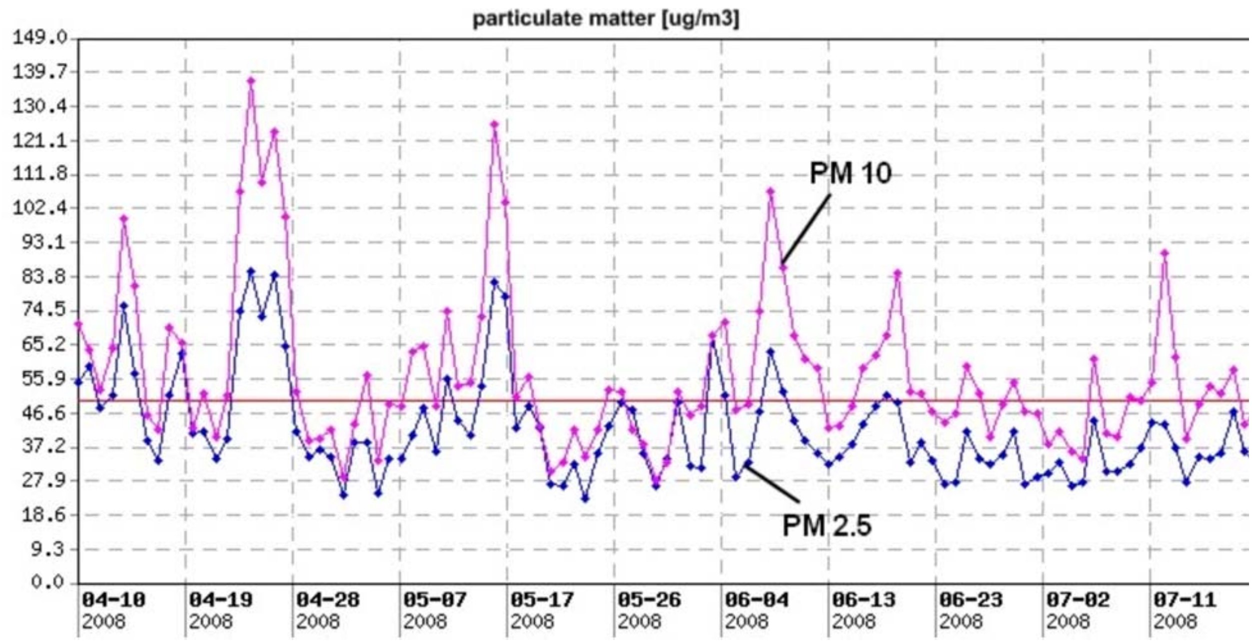

Fig. 8. Results of long term (3 months) measurements of the particulate matter (averaged for every day) with two separate instruments fitted with different samplers PM10 and PM2.5. Sampling time – 3 h. The horizontal line shows the permissible level (50 μg/m^3) of daily average particulate matter concentration.

the particulate monitor can be stored in a web page available only for the authorized users. All results: concentration of the particulate matter as well as meteorological data (temperature, pressure humidity, wind speed and direction) are stored in a file (in the text, Word and Excel format). There is also other information to be available, such as operation status, measurement mode, air pump temperature and others. Some of these parameters can be remotely changed from the monitoring centre, and others, as. e.g. faulty operation of the measuring system can be sent back from the place of installation of the gauge to the central computer and/or to the chosen mobile phone.

To demonstrate operation of the monitoring system, two examples of the obtained results from AMIZ-2007 are presented in Figs. 7 and 8. Two monitors, one with the PM10 sampler, the second with the PM 2.5 were installed in an air conditioned kiosk at Otwock, a town about 30 km to the south of Warsaw, where a limit value of PM10 is exceeded [1]. The sampling time – 3 h, Y scale – automatically adjusted to measured dust concentration. The results presented in Fig. 7 were obtained during a relatively short term of 22 days (from 10 April to 1 May 2008). In Fig. 8, there are shown the daily averaged data for a period of 99 days (from 10 April to 19 July 2008).

Beside the particulate concentration, meteorological data are also available on the same web site.

The system was installed in a few places where it operates under control of the institution responsible for environmental protection.

Conclusions

A complex system for the remote wireless monitoring of the particulate matter concentration in the ambient air was developed. The concentration monitor is operating on the beta-ray absorption principle and can be used either with the PM10 as well as with the PM2.5 sampler. Results of particulate matter concentration obtained with the PM10 sampler are generally higher than those with the PM2.5. However, in some cases, especially at low concentration of particulate mater the opposite situation can happen. This can be explained by a relatively high uncertainty of measurements occurring at low concentration of the measured particulate matter.

Analysis of the uncertainty of measurements caused by the counting statistics shows that at least a 3 h sampling time is needed to achieve a coefficient of variation lower than 20% for beta rays from Pm-147 and 10% when the C-14 beta source is applied. Derived formulae allow to asses duration of the sampling time for various values of the particulate mass in the air to get the required relative uncertainty of measurements.

Application of the C-14 beta ray source instead of the Pm-147 source improves almost two times the sensitivity of the measurement.

Generally, it seems, that the developed wireless monitoring system can deliver a huge amount of important data, which can be useful for the environmental protection services to find and identify the origin and sources of ambient air pollution.

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References

1. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe
2. ISO (2000) International Standard. Ambient air – measurements of the mass of particulate matter on a filter medium – beta-ray absorption method. ISO 10473:2000(E)
3. Johansen GA, Jackson P (2007) Radioisotope gauges for industrial process measurements, John Wiley & Sons, Ltd, Chichester
4. Naimpour MA, Rahimi H, Amini AA, Machaj B (1993) Measurements of airborne dust concentration in Tehran employing beta absorption. Nukleonika 32;2:67–78
5. PN-EN 12341:2006. Air quality – Determination of the PM 10 fraction of suspended particulate matter – Reference method and field test procedure to demonstrate reference equivalence of measurement methods
6. PN-EN 14907:2006. Ambient air quality – Standard gravimetric measurement method for the determination of the PM2.5 mass fraction of suspended particulate matter
7. Putman JL (1969) Radioisotope techniques in process control and analysis. In: Non-destructive testing. Harwell Post-Graduate Series, Oxford University Press, pp 126–131
8. Urbański P, Machaj B, Harasimczuk J, Strzałkowski J (1992) Optimization of performance of airborne dust monitors. Nukleonika 37;3:55–65