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MEASURING THE CONCENTRATION OF SUSPENDED PARTICLES (PM_{10}) IN THE INDOOR ENVIRONMENT USING THE AUTOMATIC MONITORS[***]

Abstract

The aim of this paper was to determine the applicability of the automatic monitors for measuring the indoor air pollution with suspended particles, PM_{10} fraction. The measurement results of the automatic monitor were compared with the results obtained by the reference gravimetric method. Comparative measurements over a period of 50 days were carried out during the winter of 2012 in the Laboratory of Applied Electronics in the Mining and Metallurgy Institute Bor. The analysis showed that there is a strong correlation ($R^2 = 0.61$) between the mean hourly PM_{10} concentrations, measured by the automatic monitors. The OSIRIS monitor underestimates the 24-h mean PM_{10} concentrations (the average of 30%) compared to the reference gravimetric method. Contrary to that, the EPAM-5000 monitor overestimates the 24-h mean PM_{10} concentrations (the average of 40%) compared to the reference gravimetric method. Calibration of the automatic monitors was made on the basis of the results obtained by the gravimetric method. It was determined that both examined automatic monitors are applicable for indicative measurements of PM_{10} concentrations in the indoor environment. In order to use these automatic monitors in the air pollution health impact studies, it is necessary to calibrate them, on daily basis, with the reference gravimetric method.

***Keywords:** suspended particles, gravimetry, measurement, automatic monitor*

1 INTRODUCTION

It is believed that the air quality in urban areas has a greater impact on population health than the other environmental factors, and that the ambient air pollutants are one of the most significant causes of health problems in general [1-6]. According to WHO (World Health Organization), every year over 2.7 million people dies due to the air pollution [2]. PM_{10} fraction of suspended particles (coarse particles) is primarily composed of atmospheric dust, which is caused by the mechanical crowning of granular material, for example, from paved and unpaved roads, agricultural activities, construction works and natural processes. Industrial operations like milling, grinding and other, to some extent, contribute to the fraction of coarse particles present in the ambient air [2].

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Particulate matter (PM) in the indoor air originates from the outdoor infiltration and additional indoor sources such as heating devices, cooking, tobacco smoking, etc. Automatic air particle monitors measures and records aerosol concentrations in real-time, and, therefore, it can provide insights into particulate levels and temporal variability of PM concentrations over short time intervals (a few seconds), which is not possible using gravimetric sampling methods. Numerous real-time particle monitoring and gravimetric sampling campaigns have been carried out to characterize PM mass concentrations in the indoor environment. This was done with the aim to increase the reliability and quality of information necessary for preparation the studies on the impact of particulate air pollution on human health.

In this work, the PM_{10} concentrations, obtained using the automatic monitors OSIRIS (Turnkey) and EPAM-5000 (SKC Inc.), were analyzed. Also, the average daily PM_{10} concentrations were compared with those obtained using the gravimetric method. The aim of this study was to determine whether these monitors are suitable for measuring the concentration of PM_{10} particles in the indoor environment, to study their reliability in operation and determines the deviation of their results in comparison with the reference gravimetric method.

2 MATERIALS AND METHODS

Comparative measurements of PM_{10} concentration were carried out in the period from 20.12.2011 to 15.02.2012 in the Laboratory of Applied Electronics in the Mining and Metallurgy Institute Bor. The laboratory has an approximate volume of 125 m^3, and double glass windows, with the surface of about 3 m^2. The door and windows were usually closed during the measurement campaign. The real-time aerosol monitors were placed in the center of the laboratory, at height of 1 m from the ground. A gravimetric sampler, Sven/Leckel LVS3 [7] was also placed in the laboratory next to the automatic monitors. Gravimetric samples were collected once a day (at 8 AM). Whatman QMA grade filters with the diameter of 47 mm were used for collecting the gravimetric samples. Before and after sampling, the filter mass was measured in accordance with a procedure prescribed by SRPS EN12341:2008 [8]. Based on the difference in mass of exposed and unexposed filters and known volume of air that flow through the sampler, the daily mean mass concentrations of PM_{10} were calculated.

Figure 1 *Front panel of the OSIRIS PM_{10} monitor*

The automatic monitors, used in the study, applied the light scattering technique to calculate the PM_{10} concentrations. OSIRIS (Turnkey) monitor, shown in Figure 1, is designed for the indicative measurement of PM concentration in the range of 0.5 - 20 µm [9]. EPAM-5000 (SKC Inc.) monitor, shown in Figure 2, uses the reflection of light from the particles to calculate the PM concentration per unit volume, in contrast to the OSIRIS monitor which uses the diffraction of light from the particles. EPAM-5000 is suitable for measuring the PM concentration in the range of 0.1 - 100 µm [10]. Both automatic monitors used in the study, in fact, calculate the mass concentration based on the intensity of light scattered from particles so that they have to be calibrated for each environment using the reference gravimetric method. Daily calibration is necessary because the size distribution of particles per unit of volume is time dependent. The flow rate of measuring instruments was calibrated using the certified flow meter several times during the measurement campaign, at the beginning and after every two weeks of measurements. Automatically monitors were set up to record 1-hour average concentration of PM_{10} particles. For calculation the daily averages, minimum 90% of 1-hour averages were required, otherwise, the value was considered as the missing. Visual inspection of raw data was also carried out.

Figure 2 *Front panel of the EPAM-5000 monitor*

3 RESULTS AND DISCUSSION

The regression analysis was carried out on the mean hourly PM_{10} concentrations which were measured by automatic monitors. Dispersion diagram is shown in Figure 3. It can be seen that there is a significant coincidence between the measurement results obtained by the automatic monitors. Applying the ordinary least squares linear regression, the following regression equation is obtained:

$$y = 0.468 * x - 0.71 \tag{1}$$

In the equation (1) ***y*** expresses PM_{10} concentration obtained by the OSIRIS monitor and ***x*** expresses PM_{10} concentration obtained by the EPAM-5000 monitor. Regression slope significantly different from one was considered to indicate the multiplicative bias of PM_{10} concentrations between instruments. It is obvious that the PM_{10} concentrations measured by the EPAM-5000 monitor are, on average, more than twice higher than the PM_{10} concentrations measured by the OSIRIS monitor. Regression intercept significantly different from zero was considered to indicate the additive bias of PM_{10} concentrations between instruments. The coefficient of determination (R^2) is used to describe the correlation of PM_{10} concentrations between instruments while the standard deviation is used to describe how widely values are dispersed from the average value. The coefficient of determination calculated using the correlation analysis is R^2 = 0.61. This value indicates the strong correlation between the measurement results of automatic monitors (61% of the results was explained by linear dependence).

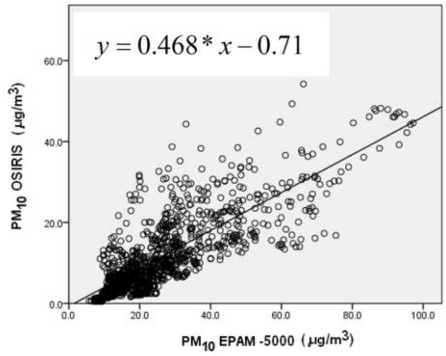

Figure 3 *Scatter plot of 1–h average PM_{10} mass concentrations, EPAM-5000 vs. OSIRIS*

The average daily PM_{10} concentrations were calculated from the 1-hour average PM_{10} concentrations. So, the obtained average daily PM_{10} concentrations were compared with the average daily PM_{10} concentrations obtained using the gravimetric method. Basic statistics for the average daily PM_{10} concentrations is shown in Table 1. Data from this table clearly indicates that the average of daily PM_{10} concentrations provided by the OSIRIS monitor is 30% lower compared to that obtained by the reference gravimetric method. In contrast, the average daily PM_{10} concentration that gives EPAM-5000 monitor is 40% higher compared to that obtained by the reference gravimetric method. It is shown in reference [11] that the average daily PM_{10} concentrations, measured by the OSIRIS monitor, were 12% lower compared to that determined by the gravimetric method. The measurements described in this reference were carried out in a room with the larger volume (175 m^3) and the room was empty of people during the campaign of measurement. In the same work, as well as in the reference [12], it was shown that the automatic monitors, using the same principle of light reflection, as EPAM-5000 use, commonly overestimate the PM_{10} and $PM_{2.5}$ concentrations in relation to those obtained by the gravimetric method (usually more than twice).

Table 1 *Statistics of 24-h average PM_{10} concentrations (µg/m^3), (SD - standard deviation)*

	PM_{10} OSIRIS	PM_{10} EPAM-5000	PM_{10} LVS3
Min	8.7	12.2	7.8
Max	25.8	53.3	48.2
Mean	14.0	27.8	19.8
SD	6.9	12.0	12.5

In order to obtain more accurate results, automatic monitors are calibrated on the basis of the PM_{10} concentrations obtained by the reference gravimetric method, using the method that is shown in the paper [12]. For each day with measurements, the calibration factor was calculated according to the following formula:

$$F = \frac{G}{S} \qquad (2)$$

In the equation (2) F is the calibration factor, G is the average daily PM_{10} concentration obtained by the gravimetric method, whilst S is the corresponding average daily PM_{10} concentration measured by the OSIRIS or EPAM-5000 monitor. The OSIRIS and EPAM-5000 measurements were normalized so that each 1-hour average PM_{10} concentration were multiplied by calibration factor F. Appearance of line charts of PM_{10} concentrations after applying the described calibration procedure is shown in Figure 4.

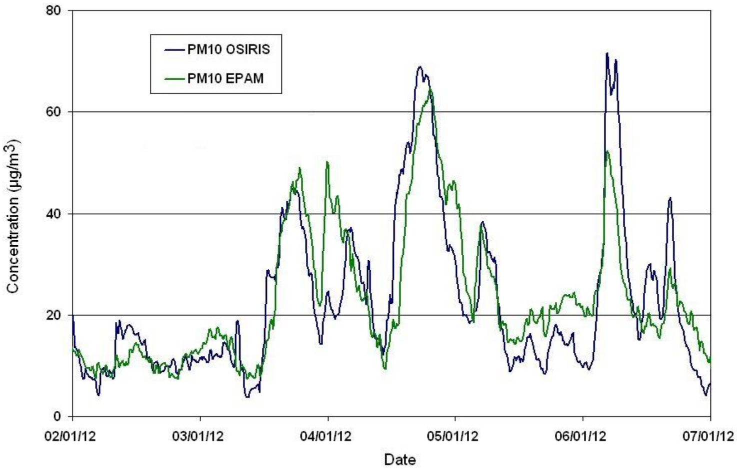

Figure 4 *Line chart of 1–h average PM_{10} mass concentrations*

4 CONCLUSION

In this work, the results of measurement of the PM_{10} concentration, using automatic monitor OSIRIS and EPAM-5000, in the indoor environment, were analyzed. The analysis showed that there is a strong correlation between the results of measurements of these automatic monitor. The linear dependence can describe/explain more than 61% of the measurement results. The average daily PM_{10} concentrations measured by the automatic monitors were compared with the average daily PM_{10} concentrations obtained by the gravimetric method. The average of daily PM_{10} concentrations provided by the OSIRIS monitor is 30% lower compared to that obtained by the reference gravimetric method. Contrary to that, the average daily PM_{10} concentration that gives EPAM-5000 monitor is 40% higher compared to that obtained by the reference gravimetric method. In order to improve the accuracy of the PM_{10} concentration readings of the automatic monitors, comparing with the results obtained by the gravimetric method, it is necessary to perform the calibration procedure on daily basis. One procedure of calibration is described in the paper. Based on the abovementioned facts, it can be concluded that the observed automatic monitors can be used for the indicative measurement of PM_{10} concentrations in the indoor environments. Both of the air particle monitors used in this study proved to be practical for PM_{10} measurements in the indoor environments, as it is small, portable, and quiet enough not to disturb the occupants of rooms where monitoring is performed. Their use allows an insight into the changes in the PM_{10} concentrations during the day, which can be helpful in identifying the sources of particles, as well as in the preparation of studies on the impact of air pollution with PM_{10} on human health.

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Viša Tasić[*], *Tatjana Apostolovski-Trujić*[*], *Renata Kovačević*[*], *Milena Jovašević–Stojanović*[**]

MERENJE KONCENTRACIJA SUSPENDOVANIH ČESTICA (PM_{10}) U UNUTRAŠNJEM PROSTORU PRIMENOM AUTOMATSKIH MONITORA[***]

Izvod

Cilj rada je da se ispita primenljivost automatskih monitora za određivanje koncentracija suspendovanih čestica frakcije PM_{10} u unutrašnjem prostoru. Rezultati merenja automatskih monitora upoređivani su sa rezultatima dobijenim referentnom gravimetrijskom metodom. Uporedna merenja, u trajanju od 50 dana, vršena su 2012 godine, tokom zime, u laboratoriji za primenjenu elektroniku Instututa za rudarstvo i metalurgiju u Boru. Analiza je pokazala da postoji jaka korelacija (R^2=0.61) između srednjih satnih koncentracija PM_{10} koje su izmerene automatskim monitorima. Srednje dnevne koncentracije PM_{10} izmerene OSIRIS monitorom u proseku su za 30% niže u odnosu na koncentracije dobijene primenom referentne gravimetrijske metode. Nasuprot tome, srednje dnevne koncentracije PM_{10} izmrene EPAM-5000 monitorom u proseku za 40% više u odnosu na koncentracije dobijene gravimetrijskom metodom. Kalibracija automatskih monitora vršena je na osnovu rezultata dobijenih gravimetrijskom metodom. Utvrđeno je da su ispitivani monitori primenljivi za indikativna merenja aerozagađenja PM_{10} česticama u unutrašnjem prostoru. Da bi se rezultati ovih automatskih monitora koristili za izradu studija o uticaju aerozagađenja na zdravlje ljudi neophodno je da se oni svakoga dana kalibrišu pomoću rezultata dobijenih referentnom gravimetrijskom metodom.

Ključne reči: *suspendovane čestice, gravimetrija, merenje, automatski monitor*

1. UVOD

Smatra se da kvalitet vazduha u urbanim sredinama ima veći uticaj na zdravlje stanovništva nego ostali faktori životne sredine, a da zagađivači ambijentalnog vazduha predstavljaju jedan od najznačajnijih uzroka zdravstvenih problema uopšte [1-6]. Prema podacima WHO (World Health Organization - Svetska Zdravstvena Organizacija) u Svetu se godišnje usled aerozagađenja dogodi preko 2.7 miliona smrtnih slučajeva [2]. Frakcija suspendovanih čestica PM_{10} **(**grube čestice**)** je prvenstveno sastavljena od atmosferske prašine koja je nastala usled mehaničkog krunjenja granularnog materijala, na primer, od asfaltiranih i neasfaltiranih puteva, poljoprivrednih aktivnosti, građevinskih radova i prirodnih procesa. Industrijske operacije kao mlevenje, brušenje i druge aktivnosti takođe u izvesnoj meri povećavaju prisustvo grubih čestica u ambijentalnom vazduhu [2].

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[***] *Ovaj rad je proistekao iz projekta br. III42008:"Unapređenje energetskih karakteristika i kvaliteta unutrašnjeg prostora u zgradama obrazovnih ustanova u Srbiji" koji je finansiran od strane Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije*

Suspendovane čestice u unutrašnjem prostoru (stambeni i poslovni objekti) potiču od infiltracije čestica iz spoljašnje sredine i nekog unutrašnjeg izvora, kao što su peći za grejanje prostorija, kuvanje ili dim od cigareta. Automatski monitori suspendovanih čestica mere i beleže koncentracije frakcija ovih čestica u realnom vremenu (npr. svakih nekoliko sekundi). Na taj način, primena ovih uređaja pruža uvid u intenzitet čestičnog zagađenja i njegovu dinamiku i u toku kratkih vremenskih intervala. Ovo nije moguće ostvariti primenom referentne gravimetrijske metode merenja. Širom Sveta sprovedene su brojne kampanje uporednih merenja koncentracija suspendovanih čestica automatskim monitorima i analizatorima u odnosu na gravimetrijsku metodu. Cilj ovih istraživanja bio je povećanje tačnosti i pouzdanosti informacija potrebnih za izradu studija o uticaju aerozagađenja suspendvanim česticama na zdravlje ljudi.

U ovom radu analizirani su rezultati merenja koncentracija suspendovanih čestica frakcije PM_{10} u unutrašnjem prostoru primenom automatskih monitora. Takođe, srednje dnevne koncentracije PM_{10} čestica, izmerene pomoću automatskih monitora, upoređivane su sa koncentracijama dobijenim gravimetrijskom metodom merenja. Korišćeni su automatski monitori tipa OSIRIS (Turnkey) i EPAM-5000 (SKC Inc.). Cilj istraživanja bio je da se ustanovi primenljivost ovih monitori za merenje koncentracija PM_{10} čestica u unutrašnjem prostoru, da se ispita njihova pouzdanost u radu, i utvrdi odstupanje njihovih rezultata u odnosu na referentnu gravimetrijsku metodu merenja.

2. MATERIJAL I METOD RADA

Uporedna merenja koncentracija PM_{10} čestica vršena su u periodu od 20.12.2011. do 15.2.2012. u laboratoriji za primenjenu elektroniku u Institutu za rudarstvo i metalurgiju u Boru. Laboratorija ima približnu zapreminu od 125 m^3. Pod laboratorije je od laminata, a prozori od duplog stakla, površine oko 3 m^2. Vrata, kao i prozori, obično su bila zatvorena tokom kampanje merenja. Automatski monitori postavljeni su u sredini laboratorije na visinu od 1 m u odnosu na pod. U njihovoj blizini postavljen je i jedan gravimetrijski sempler proizvodnje Sven / Leckel LVS3 sa glavom za uzorkovanje čestica frakcije PM_{10} [7]. Gravimetrijski uzorci uzimani su jednom dnevno (u 8 h ujutru). Za uzorkovanje su korišćeni Whatman QMA filtri prečnika 47 mm. Pre i posle uzorkovanja merena je masa filtera, saglasno proceduri propisanoj standardom SRPS EN12341:2008 [8]. Na osnovu razlike masa eksponiranih i neeksponiranih filtera i poznatog protoka vazduha kroz uzorkivač sračunate su srednje dnevne masene koncentracije suspendovanih čestica.

Sl. 1. *Izgled prednje strane OSIRIS monitora*

U eksperimentu su korišćeni automatski monitori suspendovanih čestica koji za detekciju koriste princip skretanja svetlosti (light scattering technique). OSIRIS (Turnkey) monitor, prikazan na slici 1, namenjen je za indikativna merenja koncentracija suspendovanih čestica iz opsega od 0.5 - 20 µm [9]. EPAM-5000 (SKC Inc.) monitor, prikazan na slici 2, koristi refleksiju svetlosti od čestica za izračunavanje koncentracije suspendovanih čestica u jedinici zapremine, za razliku od OSIRIS monitora koji koristi difrakciju svetlosti od čestica. EPAM-5000 je pogodan je za merenje koncentracije čestica veličine od 0.1 - 100 µm [10].

Oba monitora računaju masene koncentracije na bazi intenziteta skretanja svetlosti laserskog zraka od čestica, tako da ih treba kalibrisati za svaku sredinu u kojoj se merenja vrše, primenom referentne gravimetrijske metode. Kalibraciju je neophodno raditi svakog dana zato što je distrubucija veličine čestica u jedinici zapremine promenljiva u vremenu i veoma zavisna od lokacije na kojoj se merenje vrši. Provera protoka svih mernih instrumenata vršena je sertifikovanim meračem protoka na početku kampanje merenja, kao i svake druge nedelje tokom kampanje. Automatski monitori bili su podešeni tako da beleže srednje satne vrednosti koncentracija PM_{10} čestica.

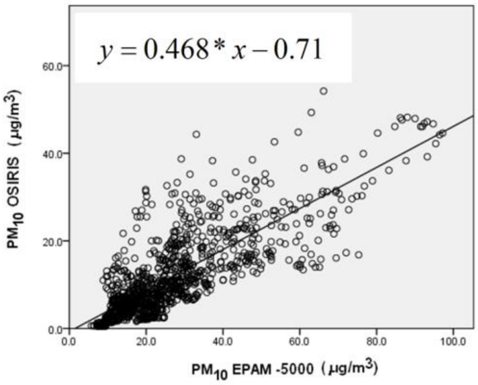
Sl. 2. *Izgled prednje strane EPAM-5000 monitora*

3. REZULTATI ISTRAŽIVANJA I DISKUSIJA

Izvršena je regresiona analiza srednjih vrednosti satnih masenih koncentracija suspendovanih čestica frakcije PM_{10} koje su izmerne pomoću automatskih monitora. Dijagram rasturanja prikazan je na slici 3. Sa ove slike može se uočiti da postoji značajna podudarnost rezultata merenja automatskih monitora. Primenom metode najmanjeg srednjeg kvadrata dobijena je sledeća regresiona jednačina:

$$y = 0.468 * x - 0.71 \quad (1)$$

U jednačini (1) ***y*** predstavlja koncentraciju PM_{10} čestica izmerenu OSIRIS monitorom, dok je ***x*** koncentracija PM_{10} čestica izmerena EPAM-5000 monitorom. Na osnovu ove jednačine može se konstantovati da su koncentracije PM_{10} čestica izmerene EPAM-5000 monitorom u proseku dva puta više od koncentracija koje su izmerene OSIRIS monitorom. Primenom korelacione analize određen je koeficijent determinacije $R^2 = 0.61$. Ova vrednost ukazuje da na to da postoji jaka korelacija rezultata merenja automatskih monitora (61% rezultata objašnjeno je pomoću linearne zavisnosti).



Sl. 3. *Dijagram rasturanja srednjih satnih koncentracija suspendovanih čestica frakcije PM_{10}, EPAM-5000 vs. OSIRIS*

Na osnovu srednje satnih vrednosti koncentracije PM_{10} čestica, koje su izmerili automatski monitori, sračunate su srednje dnevne koncentracije. Tako dobijene srednje dnevne koncentracije PM_{10} čestica upoređene su sa srednje dnevnim koncentracijama PM_{10} čestica dobijenim primenom gravimetrijske metode. Osnovna statistika srednje dnevnih vrednosti koncentracija suspendovanih čestica PM_{10} prikazana je u Tabeli 1. Iz ove tabele uočava se da su prosečne srednje dnevne koncentracije koje daje OSIRIS monitor za 30% niže u odnosu na koncentracije dobijene referentnom gravimetrijskom metodom. Suprotno tome, prosečne srednje dnevne koncentracije koje daje EPAM-5000 monitor su za 40% više u odnosu na koncentracije dobijene referentnom gravimetrijskom metodom. U referenci [11] je prikazano da su srednje dnevne vrednosti koncentracija PM_{10} čestica, merene OSIRIS monitorom, za 12% niže u odnosu na vrednosti dobijene gravimetrijskom metodom. Merenja opisana u tom radu vršena su u prostoriji veće zapremine (175 m^3) u kojoj nije bilo ljudi tokom kampanje merenja. U istom radu, kao i u radu [12], pokazano je da automatski anali-zatori, koji koriste princip refleksije svetlosti za detekciju čestica, kakav je EPAM-5000, najčešće precenjuju koncentracije suspendovanih čestica, frakcija PM_{10} i $PM_{2.5}$, u odnosu na koncentracije dobijene gravimetrijskom metodom (i više od 2 puta).

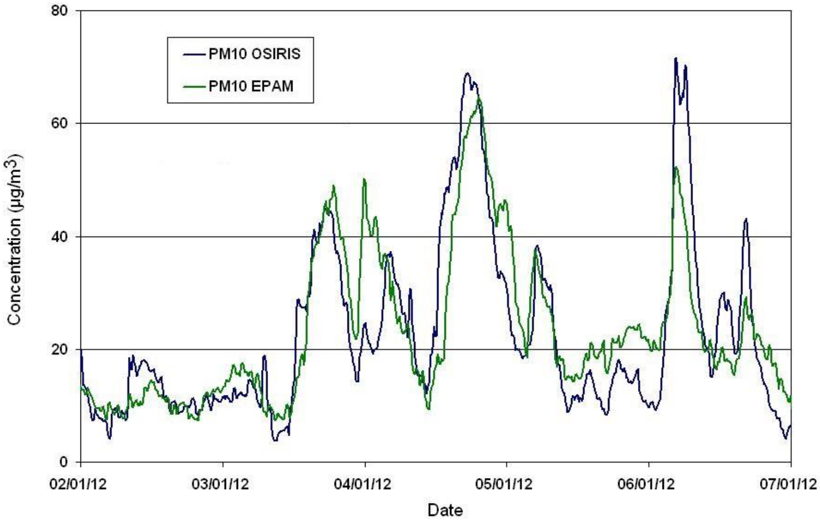
Tabela 1. *Statistika srednje dnevnih koncentracija suspendovanih čestica PM_{10} ($\mu g/m^3$), (Mean - aritmetička sredina, SD - standardna devijacija)*

	PM_{10} OSIRIS	PM_{10} EPAM-5000	PM_{10} LVS3
Min	8.7	12.2	7.8
Max	25.8	53.3	48.2
Mean	14.0	27.8	19.8
SD	6.9	12.0	12.5

Da bi se dobili tačnije vrednosti PM_{10} koncentracija u toku dana, rezultati automatskih monitora normalizovani su na bazi rezultata dobijenih referentnom gravimetrijskom metodom, primenom postupka prikazanog u radu [12]. Za svaki dan izračunat je kalibracioni faktor prema sledećoj formuli:

$$F = \frac{G}{S} \tag{2}$$

U jednačini (2) ***F*** predstavlja kalibracioni faktor, ***G*** je srednja dnevna vrednost koncentracije PM_{10} čestica dobijena gravimetrijskom metodom, a *S* je odgovarajuća srednja dnevna vrednost koncentracije PM_{10} čestica izmerena OSIRIS ili EPAM-5000 monitorom. Merenja OSIRIS i EPAM-5000 monitora su normalizovana tako što je za svaki dan sračunat kalibracioni faktor ***F***, a zatim je svaka srednje satna vrednost koncentracije PM_{10} pomnožena ovim faktorom. Izgled linijskog dijagrama koncentracija PM_{10} čestica nakon primene opisanog postupka prikazan je na slici 4.



Sl. 4. *Linijski dijagram srednje satnih vrednosti koncentracija PM_{10} čestica*

4. ZAKLJUČAK

U ovom radu analizirani su rezultati merenja koncentracija suspendovanih čestica, frakcija PM_{10}, u unutrašnjem prostoru, primenom automatskih monitora OSIRIS i EPAM-5000. Analiza je pokazala da postoji jaka korelacija između rezultata merenja ovih automatskih monitora. Linearna zavisnost može da opiše/objasni više od 61% rezultata merenja. Izvršeno je upoređivanje srednje dnevnih koncentracija PM_{10} čestica izmerenih automatskim monitorima sa srednje dnevnim koncentracijama PM_{10} čestica koje su dobijene primenom gravimetrijske metode. Srednje dnevne koncentracije PM_{10} čestica izmerene OSIRIS monitorom su za 30% niže u odnosu na koncentracije dobijene gravimetrijskom metodom. Suprotno tome, srednje dnevne koncentracije koje daje EPAM-5000 monitor za 40% su više u odnosu na koncentracije dobijene gravimetrijskom metodom. Da bi rezultati automatskih monitora PM_{10} čestica bili u saglasnosti sa rezultatima dobijenim gravimetrijskom metodom potrebno je svakodnevno vršiti njihovu kalibraciju. U radu je opisan jedan od primenjivanih postupaka za kalibraciju. Na osnovu rezultata ispitivanja automatskih monitora ustanovljeno je da su oni pogodni za indikativna merenja suspendovanih čestica frakcije PM_{10} u unutrašnjem prostoru. Njihovom primenom omogućuje se uvid u promene koncentracija suspendovanih čestica tokom dana, što može biti od velike koristi pri identifikaciji izvora ovih čestica, kao i pri izradi studija o uticaju aerozagađenja suspendovanim česticama na zdravlje ljudi.

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