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RESEARCH ON THE IMPACT OF AUTOMOTIVE SOURCES ON THE IMMISSION OF SPECIFIC SIZE FRACTIONS OF PARTICULATE MATTER IN A STREET CANYON

BADANIA WPŁYWU ŹRÓDEŁ MOTORYZACYJNYCH NA IMISJĘ FRAKCJI WYMIAROWYCH CZĄSTEK STAŁYCH W KANIONIE ULICZNYM

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Summary

The article presents results of empirical survey of the immission of specific size fractions of particulate matter as well as carbon monoxide and nitrogen oxides in the street canyon area in Warsaw in a summer month. The data characterizing the weather conditions and motor vehicle traffic intensity, collected during the survey, were also examined. The data subjected to the analysis included measurement results obtained from the "Warszawa-Komunikacyjna" Air Quality Monitoring Station in Warsaw at Aleja Niepodległości 227/233 and results of measurements carried out at the same place

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by PIMOT with the use of a TSI dust meter. The immission of the PM10, PM2.5, and PM1 particulate matter fractions was examined. It was found that automotive sources exerted a marked impact on the immission of various particulate matter size fractions, especially fine dusts. The correlational interdependence between the immission of particulate matter PM10 and the immission of nitrogen dioxide and carbon monoxide was also studied, based on results of measurements carried out at the Air Quality Monitoring Station. The correlation was found to be weak, probably because of the measurement method used. The correlational examination of the immission of individual particulate matter size fractions, based on measurement results obtained with using a dust meter, showed the correlation to be very strong. In general, pollutant emission from motor vehicles was found to have a considerable impact on the particulate matter immission in the street canyon area, especially on the immission of fine dust fractions.

Keywords: pollutant immission, particulate matter, motorization, street canyon

Streszczenie

W artykule przedstawiono wyniki badań empirycznych imisji frakcji wymiarowych pyłów oraz tlenku węgla i tlenków azotu w okolicach kanionu ulicznego w Warszawie w miesiącu letnim. Badano również wyniki charakteryzujące warunki atmosferyczne oraz natężenie ruchu samochodów. Do analizy wykorzystano wyniki badań, wykonywanych na stacji nadzorowania jakości powietrza Warszawa-Komunikacyjna przy Al. Niepodległości 227/233, oraz przeprowadzanych przy użyciu pyłomierza firmy TSI. Badano imisję frakcji wymiarowych cząstek stałych: PM10, PM2.5 i PM1. Stwierdzono wyraźny wpływ źródeł motoryzacyjnych na imisję frakcji wymiarowych pyłów, szczególnie pyłów drobnych. Badano również zależność korelacyjną imisji zanieczyszczeń cząstek stałych PM10 oraz dwutlenku azotu i tlenku węgla – na podstawie wyników badań na stacji nadzorowania jakości powietrza. Stwierdzono słabą korelację, co wynikało prawdopodobnie z zastosowanej metodyki pomiarów. Badania korelacyjne imisji frakcji wymiarowych cząstek stałych, wykonane na podstawie wyników badań wykonanych przy użyciu pyłomierza, wykazały bardzo silną korelację. Ogólnie stwierdzono istotny wpływ emisji zanieczyszczeń z pojazdów samochodowych na imisję cząstek stałych w kanionie ulicznym, szczególnie na imisje drobnych frakcji wymiarowych pyłów.

Słowa kluczowe: imisja zanieczyszczeń, cząstki stałe, motoryzacja, kanion uliczny

1. Introduction

The pollution of atmospheric air is a very serious problem, especially in large urban agglomerations. The pollutants may be both gaseous and particulate. Dust is defined as the dispersed phase of a two-phase system consisting of a solid body, i.e. small solid particles, suspended in gaseous dispersion medium. In general, dust is a mixture of particulate matter suspended in atmospheric air [5–9, 11, 15, 16].

The particulate matter may be categorized in respect of the equivalent particle size, which depends on the aerodynamic equivalent diameter (AED) of the particle. The following particulate matter fractions are usually discerned [1–5, 7, 8, 10, 11, 15–17]:

- TSP (total suspended particles), with AED below 300 μm,
- fine dust PM10, with AED below 10 μm,
- fine dust PM2.5, suspended particulate matter with AED below 2.5 μm,

– dust PM1, with AED below 1 μm, taken into consideration at the testing of internal combustion engines.

Particulate pollutants have a considerable impact on human health. This impact depends on particle size, shape, and chemical composition. The dust most dangerous to human health is the fine-grained particulate matter because it reaches the deepest portions of the human respiratory system, where it accumulates and, in a part, is absorbed. Moreover, the finest dusts penetrate into the cardiovascular system and thus, they may spread all over the organism; in particular, they may reach the brain [5, 7–9, 12, 13, 15, 16].

2. Methods of the research

The research was undertaken to assess the impact of automotive sources of pollutant emission on the values of immission of individual particulate matter size fractions in the atmospheric air in the street canyon in the Warsaw urban agglomeration.

The models of immission (I) of particulate matter PM2.5 and PM1 are built in accordance with the functional similarity criterion [1–3, 7, 8], with using the definitions of individual dust categories. The set of dusts with AED below 2.5 μm, i.e. PM2.5, is treated as a subset of the set of particulate matter with AED below 10 μm (PM10) and the particulate matter PM1 constitutes a subset of the set defined as PM2.5. The immission of particulate matter PM2.5 is modelled as linearly dependent on the immission of the PM10 dust [1–3, 5, 10, 14]:

$$I_{PM2.5} = k_{PM2.5-PM10} \cdot I_{PM10} \tag{1}$$

where $k_{PM2.5\text{-}PM10}$ – coefficient of the model of immission of the PM2.5 dust ($k_{PM2.5\text{-}PM10} \in <0;1>$).

The immission of particulate matter PM1 is modelled as linearly dependent on the PM2.5 immission [1, 3, 10, 14]:

$$I_{PM1} = k_{PM1-PM2.5} \cdot I_{PM2.5} \tag{2}$$

where $k_{PM1\text{-}PM2.5}$ – coefficient of the model of immission of the PM1 dust ($k_{PM1\text{-}PM2.5} \in <0;1>$).

The PM1 dust is also a subset of the PM10 particulate matter; therefore, its immission may also be modelled as linearly dependent on the immission of the PM10 dust [1, 3, 10, 14]:

$$I_{PM1} = k_{PM1-PM10} \cdot I_{PM10} \tag{3}$$

where $k_{PM1\text{-}PM10}$ – coefficient of the model of immission of the PM1 dust ($k_{PM1\text{-}PM10} \in <0;1>$).

The models of immission of particulate matter PM2.5 and PM1 are identified by determining the model coefficients based on results of empirical measurements [1, 3, 10, 14].

The models of immission of the PM10 particulate matter are also built in accordance with the functional similarity criterion. They include models of immission of the particulate matter with AED below 10 μm where these immission is treated as linearly dependent on the immission of nitrogen oxides (or nitrogen dioxide in some of the said models) or on the immission of carbon monoxide [3, 10, 14]:

$$I_{PM10} = a_{0NOx} + a_{1NOx} \cdot I_{NO_x} \quad (4)$$

$$I_{PM10} = a_{0CO} + a_{1CO} \cdot I_{CO} \quad (5)$$

The measuring stand was located at the "Warszawa-Komunikacyjna" Air Quality Monitoring Station operating within the State Environmental Monitoring. The Station is owned by the Provincial Inspectorate of Environmental Protection (WIOŚ) and located in Warsaw at Aleja Niepodległości 227/233 (Station code: PL0140A), in an urban area, commercial and residential zone. The Station has been situated immediately at the western carriageway of Aleja Niepodległości (leading towards the Ursynów district) [14]. The immission of the following pollutants and the following meteorological characteristics of the atmospheric air are measured at the said Station:

- nitrogen dioxide,
- carbon monoxide,
- suspended particulate matter PM10,
- suspended particulate matter PM2.5,
- benzene,
- 1,2-xylene,
- methylbenzene,
- 1,3-xylene 1,4-xylene,
- ethylbenzene,
- relative humidity,
- air temperature.

Figure 1 shows the measuring stand and the WIOŚ-owned Air Quality Monitoring Station.

Fig. 1. Photographs of the measuring stand and the Air Quality Monitoring Station of the Provincial Inspectorate of Environmental Protection (WIOŚ) [14]

Within this work, the immission of the following particulate matter size fractions was determined [14], with using a TSI dust meter, model 8533/8534 Dust Trak DRX Aerosol Monitor:

- TSP (total suspended particles), i.e. a mixture of particulate matter with equivalent particle size below 300 μm,
- particulate matter PM10 (airborne dust), i.e. particulate matter with equivalent particle size below 10 μm,
- particulate matter PM2.5 (fine dust), i.e. particulate matter with equivalent particle size below 2.5 μm,
- particulate matter PM1 (dust practically invisible to the naked eye), i.e. particulate matter with equivalent particle size below 1 μm.

The particulate matter immission was measured once per minute; then, the measurement results were averaged for a one-hour period. The scope of the survey also included measurements of motor vehicle traffic intensity, with discerning small vehicles (i.e. passenger cars – PC), large vehicles (which included light commercial vehicles – LCV, heavy duty vehicles – HDV, and buses – B), and motorcycles –Mc. The motor vehicle traffic intensity was determined by observations carried out during the pollutant immission measurements. Moreover, current weather conditions, i.e. ambient temperature, air humidity, wind velocity, and precipitations, were monitored [14].

The place of carrying out the measurements was chosen on purpose because the measurement results obtained from the Air Quality Monitoring Station were also analysed [14].

3. Results of empirical measurements

The measurements were carried out in July 2016. In this article, only selected measurement results have been presented, obtained on 5 July 2016 [14].

Figure 2 shows the immission of total suspended particles (TSP), recorded by the Dust Trak DRX Aerosol Monitor; unprocessed data have been presented. The measurements were carried out for a period of 6 h, from 8:15 a.m. till 2:15 p.m., on Tuesday 5 July 2016 [14].

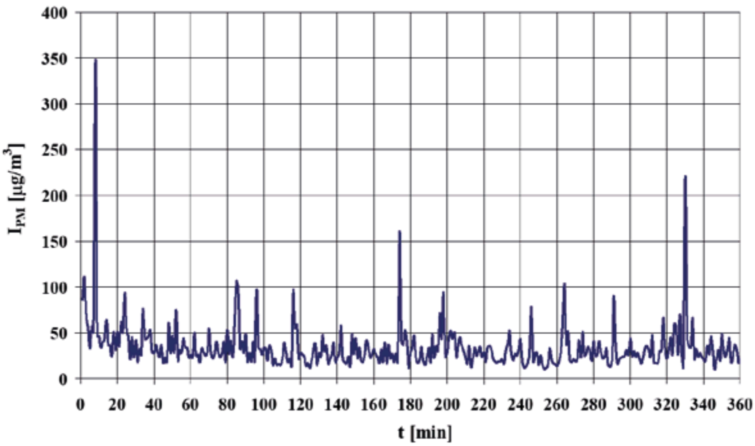

Fig. 2. The TSP immission (unprocessed data recorded by the Dust Trak DRX Aerosol Monitor) [14]

Figure 3 shows the TSP immission, recorded by the Dust Trak DRX Aerosol Monitor; the data were then smoothed by 1st-order and 2nd-order non-recursive filters for the share of high-frequency noise in the signal to be reduced [14]:

$$y(n) = \frac{1}{5}\left[x(n-2) + x(n-1) + x(n) + x(n+1) + x(n+2)\right] \tag{6}$$

$$z(n) = \frac{1}{5}\left[y(n-2) + y(n-1) + y(n) + y(n+1) + y(n+2)\right] \tag{7}$$

where: x – input signal,

y – signal processed by the 1st-order filter,

z – signal processed by the 2nd-order filter (in relation to the input signal),

n – successive number of a signal sample.

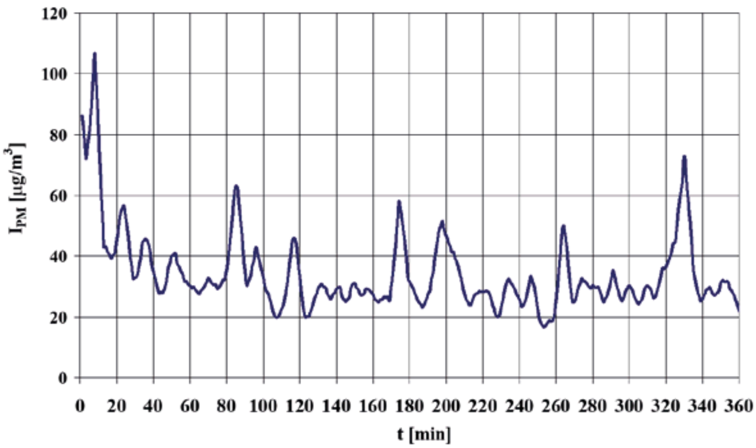

Fig. 3. The TSP immission (data recorded by the Dust Trak DRX Aerosol Monitor and smoothed by filtration) [14]

At the beginning of the measuring period, an increased value of the TSP immission was observed, which might be explained by minor traffic congestions that occurred at that time. The cyclic growths and drops in the TSP immission were caused by changing traffic lights at the intersection of Aleja Niepodległości with ulica Nowowiejska. In the curve shown in figure 3, smoothed with using the 1st-order and 2nd-order non-recursive filters, the cyclic growths and drops in the TSP immission are already not so conspicuous. The marked local peaks, such as the one around the 175th minute of the measuring period, were caused by the passage of a delivery motor vehicle that emitted a considerable amount of exhaust gases [14].

Figure 4 shows the immission of particulate matter PM1, PM2.5, and PM10, recorded by the Dust Trak DRX Aerosol Monitor; unprocessed data have been presented [14].

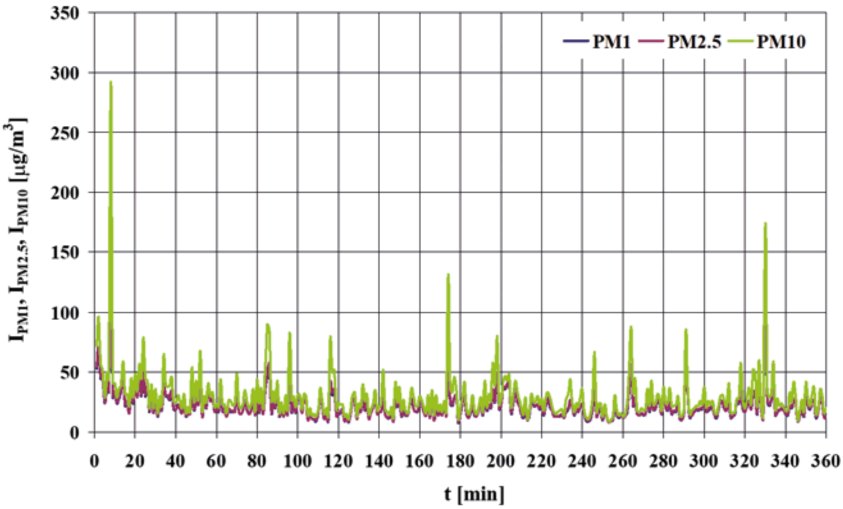

Fig. 4. The immission of particulate matter PM1, PM2.5, and PM10 (unprocessed data recorded by the Dust Trak DRX Aerosol Monitor) [14]

Figure 5 shows the immission of particulate matter PM1, PM2.5, and PM10, recorded by the Dust Trak DRX Aerosol Monitor; then, the data were smoothed by the 1st-order and 2nd-order non-recursive filters for the share of high-frequency noise in the signal to be reduced [14].

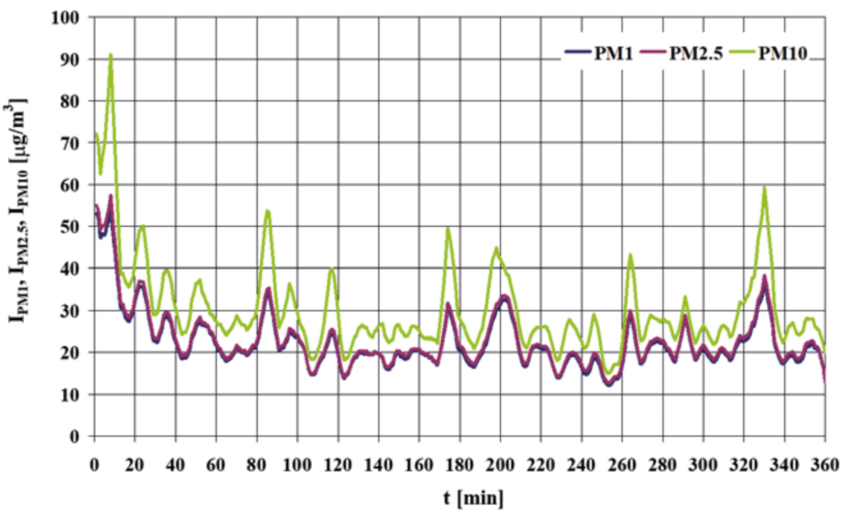

Fig. 5. The immission of particulate matter PM1, PM2.5, and PM10 (data recorded by the Dust Trak DRX Aerosol Monitor and smoothed by filtration) [14]

The immission of particulate matter PM1 and PM2.5 was found to be close to each other. The particulate matter coming from automotive sources chiefly consists of fine-grained material, i.e. the PM1 and PM2.5 dust. The immission of particulate matter PM10 was additionally affected by the secondary stirring up of dust from road surface and reserved track tramway. Such a phenomenon could actually be seen to occur during the measurements [14].

Fig. 6 shows the immission of particulate matter PM2.5 and PM10, obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station and recorded by the Dust Trak DRX Aerosol Monitor; unprocessed data have been presented [14].

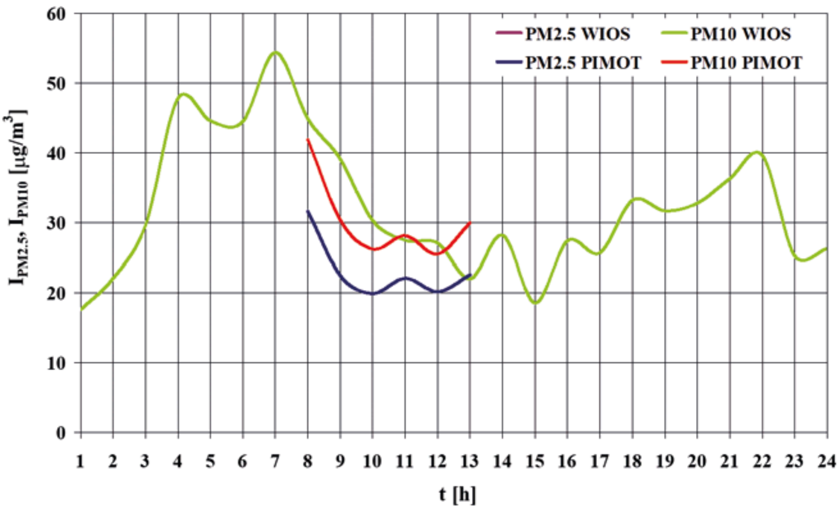

Fig. 6. The immission of particulate matter PM2.5 and PM10 (unprocessed data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station and recorded by the Dust Trak DRX Aerosol Monitor) [14]

Figure 7 shows the same immission, but the data were smoothed by the 1st-order and 2nd-order non-recursive filters [14].

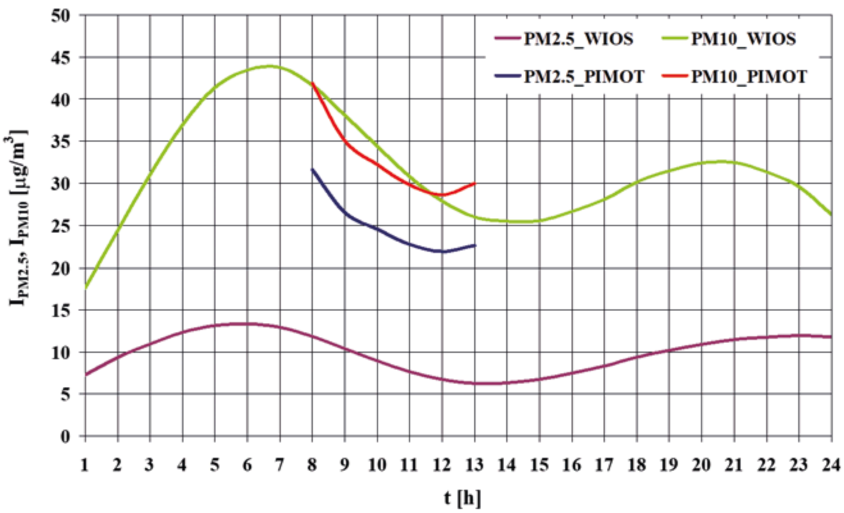

Fig. 7. The immission of particulate matter PM2.5, and PM10 (data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station and recorded by the Dust Trak DRX Aerosol Monitor; the data were smoothed by filtration) [14]

The results of measurements of the PM10 immission, obtained from the Air Quality Monitoring Station and recorded by the dust meter, do not significantly differ from each other. Conversely, big differences can be seen in the case of particulate matter PM2.5. The reasons for such a finding are difficult for identifying; undoubtedly, however, the very low PM2.5 immission in comparison with the immission of the PM10 dust as reported by the Air Quality Monitoring Station is not typical for the pollutants emitted from automotive sources. For such pollutants, the very fine dust predominates in the whole set of particulate matter [1–3, 5, 7, 8, 10], as it can be seen in the measurement results obtained from the Dust Trak DRX Aerosol Monitor.

Raised PM2.5 and PM10 immission was observed in the morning rush hours; moreover, they were higher again between 8 p.m. and 10 p.m., i.e. after the evening rush hours.

The scope of the survey also included the observation of current weather conditions such as ambient temperature, air humidity, wind velocity, and precipitations. The air temperature and humidity measurement results were obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station. The wind velocity was measured with using a TSI thermal anemometer model 9535 VelociCalc [14].

The results of measurements of temperature (T) and relative humidity (w) of the ambient air have been presented in figure 8.

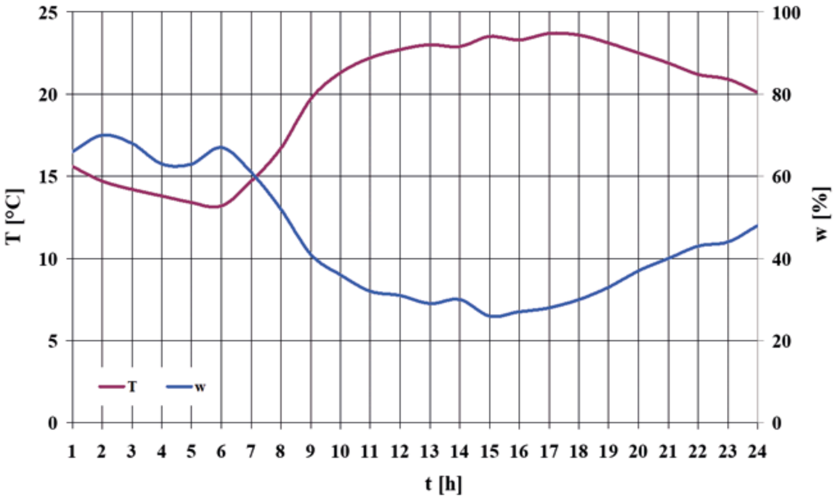

Fig. 8. The temperature (T) and relative humidity (w) of the ambient air (data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station) [14]

On the day when the measurements were carried out, the ambient temperature was within a range of (13 ÷ 24) °C and the relative humidity varied between 26% and 70%. The average temperature and humidity values did not exceed 20 °C and 45%, respectively. The air temperature and humidity on that day did not have a considerable impact on the particulate matter immission values [14].

The results of measurement of wind velocity and ambient air temperature have been presented in table. Unfortunately, the measurements were not continuously carried out because of limited capabilities of the test equipment available [14].

Table. Wind velocity and ambient air temperature [14]

Time	Wind velocity	Air temperature
h:min:s	m/s	°C
08:16:58	1.67	23.6
08:17:13	1.6	23
08:17:28	0.89	22.8
08:17:55	0.97	22.6
08:18:10	1.12	22.3
09:24:05	1.53	25.8
09:24:20	0.57	24.7
09:24:38	0.82	24.1

Time	Wind velocity	Air temperature
h:min:s	m/s	°C
11:05:32	0.95	28.7
11:05:58	0.17	28.7
11:21:00	0.59	32
11:21:25	0.66	30.7
11:21:48	1.59	27.7
11:22:29	0.55	25.7
12:04:05	1.08	27.5
12:04:26	0.66	26.7

09:24:54	0.65	24	13:16:16	0.63	26.5
11:04:16	0.49	28.4	13:16:50	0.32	26.3
11:04:31	1.69	28.6	13:17:07	0.78	26.2
11:04:47	1.33	28.7	14:04:13	1.33	25.9
11:05:02	1.31	28.7	14:04:31	0.74	25.4
11:05:16	0.76	28.7	08:19:52	0.52	23.1

The average wind velocity was about 0.68 m/s and the wind velocity range was 1.52 m/s. The average air temperature was 27.7 °C and the air temperature range was 9.7 °C. Based on the previous experience gained in the research on particulate matter immission, an assumption may be made that on that day, neither the wind velocity nor the air temperature had any considerable impact on the particulate matter immission values [14].

The scope of the survey also included measurements of motor vehicle traffic intensity N [V/h] (here: V is the number of vehicles) at the place of the measurements. The vehicles moving along Aleja Niepodległości were divided into three groups: the first one consisted of passenger cars – PC, the second one included light commercial vehicles – LCV (i.e. light trucks and delivery vehicles), heavy-duty vehicles – HDV, and buses – B, and the third one comprised motorcycles – Mc. The observations were simultaneously carried out at two carriageways: one leading towards the city centre ("Centrum") and the other one leading in the opposite direction, i.e. towards the Ursynów district. The observation results have been presented in figure 9 [14].

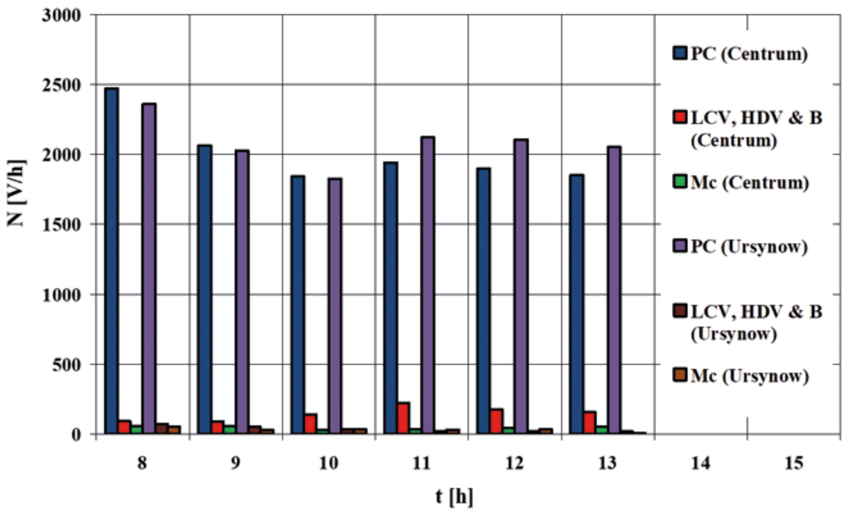

Fig. 9. Intensity of the vehicle traffic in both directions of Aleja Niepodległości [14]

When analysing figure 9, one can notice that both towards the city centre ("Centrum") and towards the Ursynów district, the most vehicles moved in the morning hours, i.e. between

8 a.m. and 9 a.m. The particulate matter immission also reached the highest values during the first hours of carrying out the measurements. This shows that the particulate matter present in the atmosphere in that area was chiefly emitted from motor vehicle traffic [14].

4. Examination of the correlation between the immission of particulate matter PM10 and the immission of nitrogen dioxide and carbon monoxide

The immission of particulate matter PM10 together with the immission of carbon monoxide – CO and nitrogen dioxide – NO_2 have been presented in figure 10. The data were obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station and then the resulting curves were smoothed by the 1st-order and 2nd-order non-recursive filters [14].

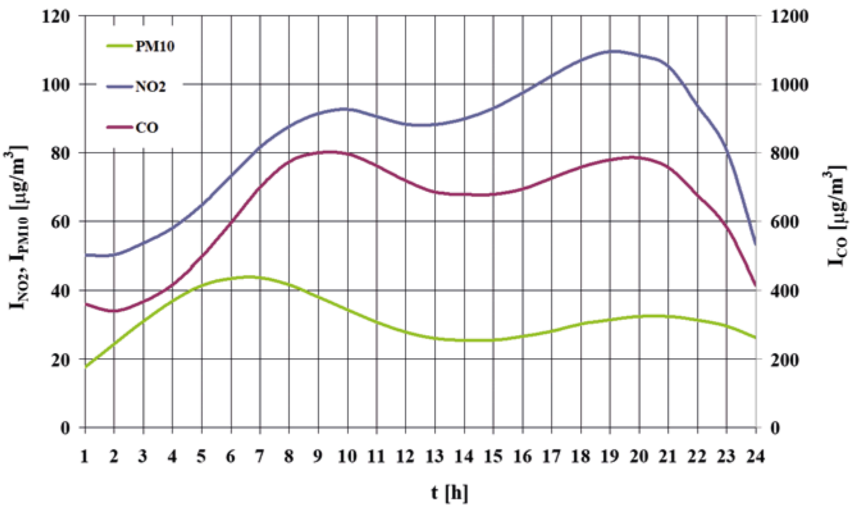

Fig. 10. The immission of particulate matter PM10, carbon monoxide, and nitrogen dioxide (data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station) [14]

The curves in figure 10 indicate that the immission of carbon monoxide and nitrogen dioxide grew during both the morning and afternoon rush hours [14].

Correlational interdependences between the immission of particulate matter PM10 and carbon monoxide as well as between the immission of particulate matter PM10 and nitrogen dioxide have been presented in figures 11 and 12. The data were obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station [14].

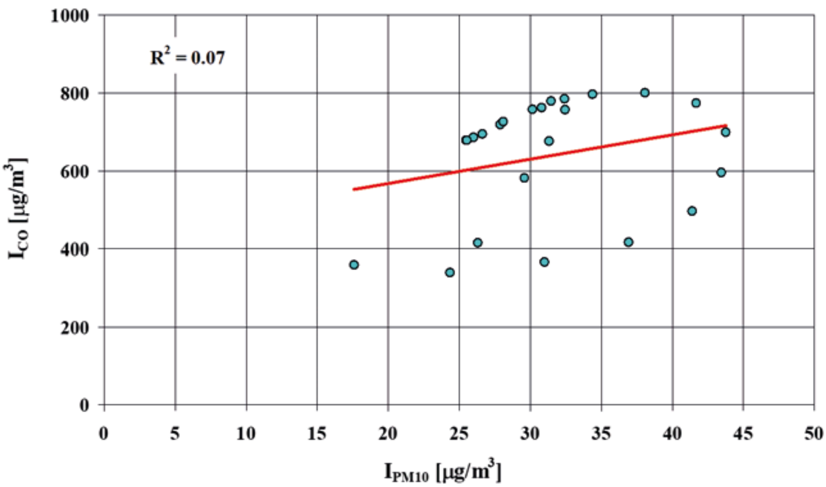

Fig. 11. Correlational interdependence between the immission of particulate matter PM10 and carbon monoxide (data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station) [14]

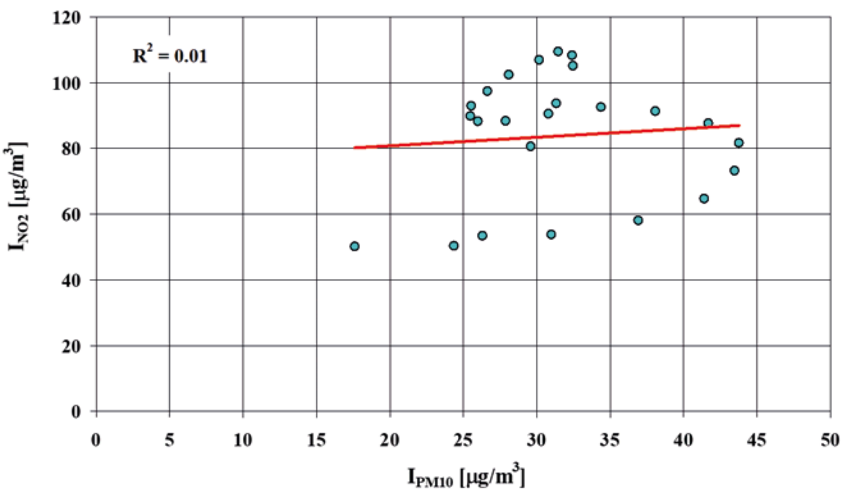

Fig. 12. Correlational interdependence between the immission of particulate matter PM10 and nitrogen dioxide (data obtained from the "Warszawa-Komunikacyjna" WIOŚ-owned Air Quality Monitoring Station) [14]

An analysis of the results presented in figures 11 and 12 did not reveal any considerable correlation between the immission of particulate matter PM10 and carbon monoxide: the value of the coefficient of determination was $R^2 = 0.07$. No correlation was observed, either, between the immission of particulate matter PM10 and nitrogen dioxide: in this case, the value of the coefficient of determination was $R^2 = 0.01$ [14].

These results of the correlational examination of the immission of particulate matter PM10 and the immission of nitrogen dioxide and carbon monoxide, showing the correlation to be weak, may be explained by random errors caused by significant dispersion of the pollutants in the samples taken for measurements as well as by insufficient observation time.

5. Coefficients of the model of immission of specific size fractions of particulate matter

Figures 13 and 14 show processes and mean values of individual coefficients of the model of immission of specific size fractions of particulate matter [14].

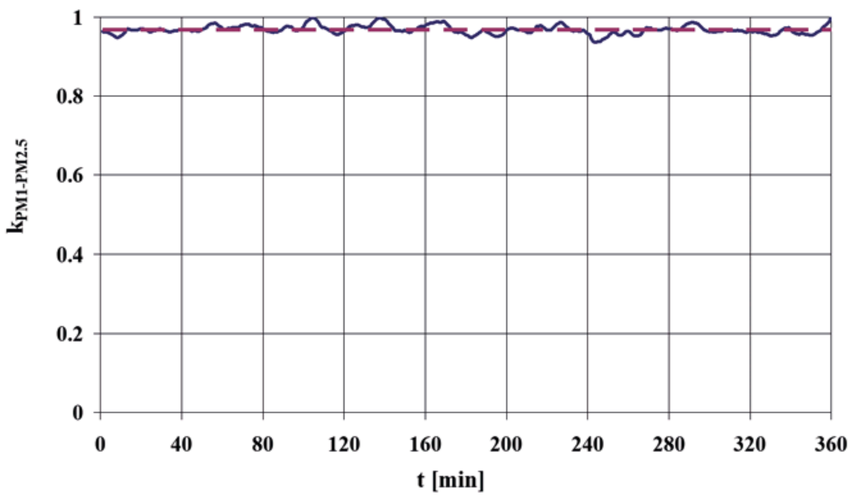

Fig. 13. Coefficient $k_{PM1-PM2.5}$ (data obtained from the Dust Trak DRX Aerosol Monitor) [14]

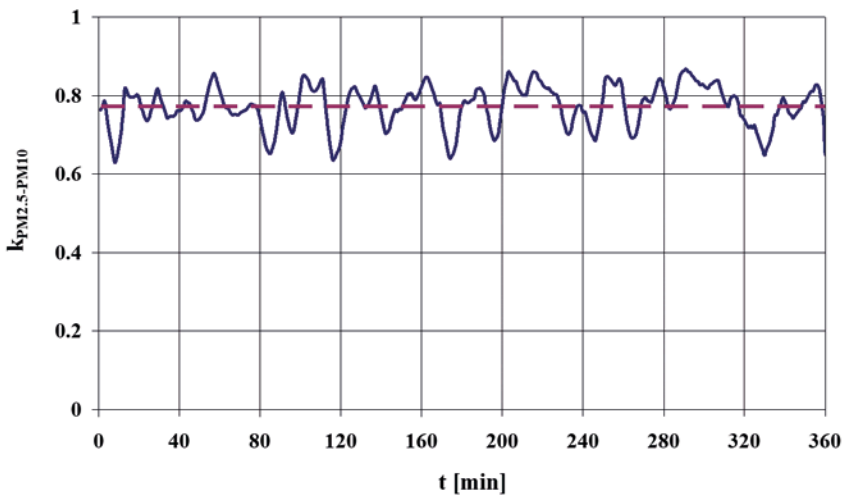

Fig. 14. Coefficient $k_{PM2.5\text{-}PM10}$ (data obtained from the Dust Trak DRX Aerosol Monitor) [14]

An analysis of the curves in figures 13 and 14 indicated that the mean value of the coefficient for the model of immission of particulate matter PM1 was high, exceeding 0.95 (data obtained from the Dust Trak DRX Aerosol Monitor). For the model of immission of particulate matter PM2.5, the mean value of the coefficient exceeded 0.75 (data obtained from the Dust Trak DRX Aerosol Monitor) [14].

6. Recapitulation

The research was undertaken to assess the impact of automotive sources of pollutant emission on the values of immission of individual particulate matter size fractions in the atmospheric air in the street canyon in the Warsaw urban agglomeration [14].

The time of carrying out the measurements, i.e. summer season, was chosen on purpose because the air pollution by heating sources is then lower, thanks to which the impact of automotive sources on atmospheric pollution could be presented in a more selective way.

An analysis of the research results has made it possible to ascertain that the immission of particulate matter increases with growing intensity of motor vehicle traffic. It can be seen from the measurement results obtained from the Dust Trak DRX Aerosol Monitor how significant impact is exerted by automotive sources on the values of immission of such pollutants in the atmosphere. Particularly conspicuous were both the cyclic growths and drops in the particulate matter immission resulting from changes in traffic lights' signals and the temporary immission peaks caused by the passage of motor vehicles that emitted a considerable amount of exhaust gases, which could be observed during the measurements [14].

Regrettably, the impact of automotive sources on the values of immission of individual particulate matter size fractions in the atmospheric air could only be roughly estimated on the grounds of the measurements carried out, chiefly because of too short a time of the measurements, but also due to the fact that the measurements were carried out in summer season, when the traffic intensity is reduced [14].

To sum up: the intensity and type of motor vehicle traffic close to air quality monitoring stations should be examined systematically; moreover, the impact of weather conditions on the pollutant immission measurement results should be analysed as well.

In spite of a limited scope of the research carried out, a statement may be made on these grounds that the automotive sources have a significant impact on the air quality in the surroundings and, in consequence, on the health of inhabitants of urban agglomerations [14].

The full text of the article is available in Polish online on the website http://archiwummotoryzacji.pl.

Tekst artykułu w polskiej wersji językowej dostępny jest na stronie http://archiwummotoryzacji.pl.

References

[1] Chłopek Z. Testing of hazards to the environment caused by particulate matter during use of vehicles. Eksploatacja i Niezawodnosc – Maintenance and Reliability. 2012; 2: 160–170.

[2] Chłopek Z. Ocena stanu zagrożenia środowiska przez cząstki stałe PM2,5 ze źródeł transportu drogowego (Evaluation of the state of threat to the environment by the PM2,5 particulates from the road transport sources). Proceedings of the Institute of Vehicles / Warsaw University of Technology. 2011; 82 (1): 101–110.

[3] Chłopek Z. Modelowanie emisji cząstek stałych PM10 ze źródeł motoryzacyjnych do celów oceny oddziaływania transportu drogowego na środowisko (Modelling of the emission of particulate matter PM10 from automotive sources for the purposes of environmental impact assessment of road transport). Report of research project No. N N509 083637 sponsored by the Ministry of Science and Higher Education, Warszawa 2012.

[4] Chłopek Z, Jakubowski A. A study of the particulate matter emission from the braking systems of motor vehicles. Eksploatacja i Niezawodnosc – Maintenance and Reliability. 2009; 4: 45–52.

[5] Chłopek Z, Skibiński F. Wprowadzenie w tematykę emisji cząstek stałych PM2,5 powodowanych transportem samochodowym (Introduction to the subject of the particulate matter emission PM2,5, from the road transport). Transport Samochodowy – Motor Transport. 2010; 3: 73–87.

[6] Chłopek Z, Suchocka K. Analiza przepisów ochrony środowiska przed emisją cząstek stałych w aspekcie ruchu samochodowego (The analysis of environmental protection regulations against particulate matter emission in terms of traffic). Proceedings of the Institute of Vehicles / Warsaw University of Technology. 2014; 97 (1): 21–32.

[7] Chłopek Z, Suchocka K. Modelowanie emisji i imisji frakcji wymiarowych cząstek stałych związanych z ruchem samochodowym (The modeling of emission and immission of particulate matter size fraction related to vehicle traffic). Proceedings of the Institute of Vehicles / Warsaw University of Technology. 2014; 97 (1): 5–20.

[8] Chłopek Z, Suchocka K. Risks posed by particulate matter to the human health and environment near transport routes. The Archives of Automotive Engineering – Archiwum Motoryzacji. 2014; 63 (1): 3–24 and 109–129.

[9] Chłopek Z, Suchocka K, Dudek M, Jakubowski A. Hazards posed by polycyclic aromatic hydrocarbons contained in the dusts emitted from motor vehicle braking systems. Archives of Environmental Protection. 2016; 42 (3): 3–10.

[10] Chłopek Z, Szczepański T. Ocena zagrożenia środowiska cząstkami stałymi ze źródeł cywilizacyjnych (Environmental risk assessment of particulate matter from civilization sources). Inżynieria Ekologiczna. 2012; 30.

[11] Juda-Rezler K. Oddziaływanie zanieczyszczeń powietrza na środowisko (Environmental impact of air pollutants). Oficyna Wydawnicza Politechniki Warszawskiej (Publishing House of the Warsaw University of Technology). Warszawa 2000.

[12] Siemiński M. Środowiskowe zagrożenia zdrowia (Environmental health risk). Wydawnictwo Naukowe PWN. Warszawa 2001.

[13] Sroczyński J. Wpływ zanieczyszczeń powietrza atmosferycznego na zdrowie ludzi (The impact of atmospheric air pollution on human health). Ossolineum Publishing House at the Polish Academy of Sciences. Wrocław 1989.

[14] Strzałkowska K. Sprawozdanie z zadania nr DDS-117-BLM Badania wpływu źródeł motoryzacyjnych na wartość imisji frakcji wymiarowych cząstek stałych w aglomeracji warszawskiej (Report of Project No DDS-117-BLM "Research on the impact of automotive sources on the values of immission of specific particulate matter size fractions in the Warsaw urban agglomeration"). Warszawa 2016.

[15] Suchocka K. Modelowanie imisji cząstek stałych PM2.5 ze źródeł motoryzacyjnych (Modelling of the immission of particulate matter PM2.5 from automotive sources). Engineer's (Bachelor's) graduation work. Warszawa 2012.

[16] Suchocka K. Modelowanie imisji frakcji wymiarowych cząstek stałych ze względu na oddziaływanie motoryzacji na środowisko (Modelling of the immission of specific particulate matter size fractions in respect of the environmental impact of motorization). Master's graduation work. Warszawa 2013.

[17] Żegota M. Modelowanie emisji cząstek stałych PM10 z pojazdów samochodowych (Modelling of the emission of particulate matter PM10 from motor vehicles). Doctoral dissertation. Warsaw University of Technology 2006.