Effect of wind speed on the level of particulate matter PM10 concentration in atmospheric air during winter season in vicinity of large combustion plant

Robert Cichowicz¹ · Grzegorz Wielgoński² · Wojciech Fetter³

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Abstract

The concentrations of suspended particulate matter PM10 in two-month winter period, i.e. December–January in years 2009–2015, were analyzed in relation to the values of wind speed in that time. It was possible to analyze results of air pollution measurements performed in the measuring station from the perspective of their higher levels in winter seasons (so-called smog episodes). Results from 3 stations of the Regional Inspectorate for Environmental Protection in Poznań (WIOŚ Poznań) served for better presentation of smog episodes in the region (black smog) and aimed at verification of correctness of the measurements of pollution immission in the monitoring station in Piotrkowice which is situated in vicinity of large combustion plant. The analysis confirmed that with low speeds of wind higher values of particulate matter PM10 were observed. The results of the analysis also show the displacement of pollutants according to the current wind direction or their local persistence for a longer time over one area.

Keywords Air quality · Smog episodes · Particulate matter PM10 · Wind speed

1 Introduction

Air quality and pollution levels are a problem not only in industrial and highly urbanized areas but also in typical agricultural areas. This is due to the spread of pollution (without any restrictions) according to the direction of wind affecting the area. For this reason it is important

✉ Robert Cichowicz
ROBERT.CICHOWICZ@P.LODZ.PL

¹ Faculty of Architecture, Civil and Environmental Engineering, Lodz University of Technology, Al. Politechniki 6, 90-924 Lodz, Poland

² Faculty of Process and Environmental Engineering, Lodz University of Technology, Wolczanska 175, 90-924 Lodz, Poland

³ Department of Environmental Protection of Pątnów-Adamów-Konin Power Complex S. A, Kazimierska 45, 62-510 Konin, Poland

to analyze both the size and extent of the pollution. Without the determination of these quantities it is not possible to carry out appropriate measures that may be aimed at improving the state of environment (Cichowicz and Wielgosiński 2015a, 2015b; Deligiorgi et al. 2013; EEA Report No 28 2016; Moreira and Vilhena 2009; Turner 1994).

Among atmospheric pollutants, unfortunately, there are also particles of both PM10 and PM2.5 whose presence may have a negative impact on human health. It is known that even brief exposure to very fine particles of suspended particulate matter can lead to some adverse changes in the human body (Samet et al. 2009; Brook et al. 2014; Huang et al. 2012). Particularly high amounts of particulate matter are emitted from the chemical, mining, metallurgical and construction industries (cement production) and, above all, as a result of the activity of power plants. For this reason both the concentration of particulate matter and its precipitation are important indicators of atmospheric pollution. However, not only its concentration determines its harmfulness, but also chemical and mineralogical composition (Seaton et al. 1995; Kampa and Castanas 2008).

Suspended particulate matter is also responsible for the so-called smog, which is a combination of mist and atmospheric pollutants, and is produced in an unnatural way and occurs primarily over large industrialized urban agglomerations. As an essential component of smog, suspended particulate matter is mostly found in London acid smog and slightly in photochemical smog (Los Angeles type) (Makhiniashvili and Makles 2006). In Poland, smog episodes will appear for a few years every winter. In fact this is a slightly different kind of smog from the one described in the literature of acidic smog called London type. The winter smog occurring in Poland is closely related to the so-called low emission coming from individual heating systems in the city centers and it consists of dust in from PM10 and polyaromatic hydrocarbons, especially benzo(a)pyrene. Additionally, in the winter season in Poland, especially in Polish towns, smog episodes i.e. extremely high mass concentrations of particulate matter PM10 and PM2.5 are observed in high-altitude weather, with negative temperatures, low wind and temperature inversion, at the inflow of cold air from the east. These are completely different atmospheric conditions from the conditions occurring during the so-called London-type smog.

2 Experimental

The analysis covered data from the two-month winter period, i.e. December–January in years 2009–2015, for PM10 particulate matter that came from an automatic atmospheric air monitoring station located in Poland in eastern Wielkopolska in Konin Region in the municipality of Ślesin, in Piotrkowice located near large combustion plants. PM10 concentrations were also compared with wind speed values and data from 3 stations of the Voivodship Inspectorate for Environmental Protection (Poznań-Botanik station, Poznań-Polanka station and Konin-Wyszyński station), two located in the large city (Poznań, about 100 km from Piotrkowice station) and one in a nearby city (Konin).

The largest plants affecting the quality of atmospheric air of the Konin Region are power plants forming the Pątnów-Adamów-Konin Complex Power Plant S.A. (ZE PAK S.A.) (Fig. 1) the aluminum smelter (Impexmetal S.A. Aluminum Konin) and municipal solid waste incinerator (Municipal Waste-to-Energy Plant). The Piotrkowice station lies on the dominant

wind direction compared to the Patnów power plant (part of ZE PAK). In addition, the level of particulate matter is also affected by the agricultural sector (the area surrounding the arable land accounts for almost 55% of the total area of the district) and the municipal sector (Zarzycki et al. 2007).

PM₁₀ particulate measurement was carried out using a TEOM 1400a analyzer produced by Rupprecht & Patashnick Co, currently Thermo Scientific (with a concentration range of 5 µg/m³ to several mg/m³) placed in a container. The analyzer consists of a control element, measuring head and air intake (the tested air is taken from the outside by an air intake which, thanks to its design, ensures the intake of particulate matter with a size smaller than 10 µm. Next, the air sample is heated in the measuring head to 50 °C and then directed to the measuring filter at a flow rate of 3 l/min. The filter, on which particulate matter is collected, is placed on the head, which is a thin glass tube subjected to vibrations at a specified frequency. The change in vibration frequency of the head and the filter is proportional to the mass increase of the particulate matter deposited on the filter. The more particulate matter appears on the measuring filter per time unit, the lower the vibration frequency of the head and the higher the particulate matter concentration recorded by the analyzer. The control unit regulates the vibration frequency of the head and filter, air sample flow, its temperature and degree of filling the filter). Sensors mounted in meteorological radiation shields with accuracy of ±0.2 °C and ±1% RH (at +20.0 °C) were used to measure air temperature and humidity (Vaisala HMP 45A sensor, Pt1000 sensor and HUMICAP 180 sensor). Additionally, to measure the direction and

Fig. 1 Location of power plants forming the Patnów-Adamów-Konin Complex Power Plant S.A. (QGIS version 2.18.19)

velocity of wind, an anemometric sensor was installed at the top of the 12 m meteorological mast which had no moving parts and was resistant to adverse weather conditions. In summary, the measuring stations were equipped with analyzers for continuous pollution measurements, and the PM₁₀ measurements were based on a method equivalent to the reference method and recognized by the European Commission, i.e. a method of beta-ray weakening (accordance with the reference methods specified in Annex VI of the CAFE Directive). On the other hand, the accuracy of indications of the HMP 45A sensor installed permanently on the station was periodically checked by comparing with the indications of an identical device, which is a measuring element of a portable temperature and humidity meter of the same company, calibrated every two years at the Central Office of Measures. All devices worked at stations in a round-the-clock manner on all days of the year with small interruptions (about 1% of the time), dedicated to servicing and calibration.

3 Results and discussion

The choice to analyze PM₁₀ was due to the fact that it is one of the two main atmospheric pollutants (sulfur dioxide and particulate matter) whose levels are the highest during the winter. At the same time, in “favorable” meteorological conditions (mainly inversion of air temperature and weak wind) and high emission of pollutants, particulate matter can cause the so-called “black smog” (Jeż 2009) which means accumulation of pollutants in the atmosphere for a longer period of time (up to a few days). Therefore, PM₁₀ measurements and meteorological data were chosen for analysis, and it was assumed that the variability of PM₁₀ levels would be most apparent in relation to wind direction and speed as well as air temperature and humidity. Based on the above assumptions, the results of PM₁₀ measurements in the Piotrkowice station (Fig. 2) and selected three stations of the Regional Inspectorate for Environmental Protection in Poznań were analyzed: Konin, ul. Wyszyńskiego 3a (referred to as “Konin-Wyszyński”); Poznań, ul. Polanka 24 (referred to as “Poznań-Polanka”); Poznań, ul. Dąbrowskiego 169 (referred to as “Poznań-Botanik”).

Atmospheric air monitoring station “Piotrkowice-Konin” is surrounded mainly by arable fields and meadows. From the east and south there are forests occupying 21% of the whole

Fig. 2 Location of automatic monitoring stations. (<https://www.google.pl/maps/@52.3537164,17.6563638,10.05z>)

area of the Ślesin Municipality (Konin Region), where the analyzed measurement station is located. At the same time, the nearest human settlements are located in the following distances: 0.6 km to the village of Piotrkowice (532 inhabitants), 1.5 km to the village of Wygoda (270 inhabitants), 2.1 km to the village of Niedźwiady Duże (163 inhabitants) and 3.1 km to the village of Półwiosek Stary (263 inhabitants) and approx. 3.5 km to the city of Ślesin (about 3200 inhabitants) and 4.2 km to the village of Licheń (about 1500 inhabitants). The stations of the Provincial Environmental Protection Inspectorate in Poznań are located within 2 large settlements (in cities with more than 50,000 inhabitants and a population density above 1500 persons/km², applies to both stations in Poznań) and one medium-sized town (5000 to 50,000 inhabitants and population density from 300 to 1500 people/km², applies to Konin). The settlement classification was adopted in accordance with the definition of “Organization for Economic Cooperation and Development” and “European Commission – OECD-EC (Dijkstra and Poelman 2012; Servillo et al. 2014).

Results for PM₁₀ from air monitoring stations of the Voivodship Inspectorate for Environmental Protection in Poznań taken into account in the analysis, were used to compare the level of this pollution with the results obtained in the Piotrkowice station and helped us to determine its occurrence at the same time on a larger area.

In Table 1 presents information on the number of days during which smog episodes occurred. Figures 3, 4 and 5 show the distributions of PM₁₀ concentrations depending on wind speed; the results presented relate to the average daily value of PM₁₀ and wind speed. In these drawings, the results of PM₁₀ suspended particulate concentrations from the monitoring station in Piotrkowice were marked as yellow columns with the term “Piotrkowice”, while the results from the station of the Regional Inspectorate for Environmental Protection were shown as dots in green, blue and purple, marked in the legend of “Poznań-Botanik”, “Poznań-Polanka” and “Konin-Wyszyński”.

Monitoring stations in Poznań, located in large settlements, recorded significantly more smog days, with exceeded permissible levels of suspended particulate matter in the air than Station Piotrkowice located outside the city, in the area of village. This confirms the thesis that the main source of air pollution are low emissions from individual heating systems which dominate the city. In the area village Piotrkowice its air quality is much better, even in periods that are particularly conducive to smog formation.

The values of temperature and humidity are shown below in Tables 2 and 3 as 24-h averaged results for each month. Then, the average values for each month over the period considered, i.e. from 2009 to 2015, were calculated. To illustrate calculations, in the case of temperature, the function “conditional formatting” was used to obtain the colors presented in Table 2. At the same time, it was assumed that the height of the “bar” means the absolute value of temperature, while the blue color refers to the negative temperatures and the red ones are

Table 1 Number of smog days from the two-month winter period, i.e. December–January in years 2009–2015

Year	Station Piotrkowice	Station Konin-Wyszyński	Station Poznań-Polanka	Station Poznań-Botanik
2009–2010	14	14	31	36
2010–2011	7	14	23	29
2011–2012	1	1	12	14
2012–2013	15	30	31	22
2013–2014	4	10	16	8
2014–2015	2	13	12	15

Fig. 3 PM10 particulate matter concentration depending on wind speed in December 2009 and January 2010 and in December 2010 and January 2011

Fig. 4 PM10 particulate matter concentration depending on wind speed in December 2011 and January 2012 and in December 2012 and January 2013

Fig. 5 PM10 particulate matter concentration depending on wind speed in December 2013 and January 2014 and in December 2014 and January 2015

Table 2 Mean temperature values [°C] in months and years 2009–2015 (Monitoring Station Piotrkowice)

year month	2009	2010	2011	2012	2013	2014	2015	average
January	−2,8	−7,0	−0,1	0,2	−3,3	−1,9	1,5	−1,9
February	−0,2	−1,2	−4,0	−6,4	−0,5	2,9	0,9	−1,2
March	3,4	4,1	2,8	5,4	−2,4	6,4	5,2	3,6
April	11,6	9,3	11,3	8,4	7,6	11,0	8,4	9,7
May	13,7	13,2	15,2	17,1	15,2	14,2	13,8	14,6
June	15,8	17,4	19,4	16,7	19,0	17,4	17,4	17,6
July	19,7	22,6	19,1	21,3	20,4	22,8	20,8	21,0
August	19,6	20,1	20,1	20,0	20,1	19,1	23,4	20,3
September	15,7	13,1	16,0	15,3	13,3	16,3	16,3	15,1
October	7,5	6,4	10,1	9,2	10,6	11,1	8,0	9,0
November	5,9	5,9	4,0	5,7	5,5	6,1	6,0	5,6
December	−0,6	−6,6	3,3	−1,9	2,8	1,3	5,8	0,6

positive. However, the color of cells in Table 3 was determined in such a way that the highest values (i.e. the air with the highest humidity percentage) were dark blue, and the lowest values (the smallest humidity) were marked in red.

As a result, differences between the individual temperatures (Table 2) in subsequent years and the average which they determine, as well as differences between average temperatures in each year were distinguished. In the same way air humidity was analyzed (Table 3) and reduced through averaging to mean monthly values from the subsequent years and from the seven-year period. Due to such analysis of results we can find that there are months or groups of months with periods of similar humidity (dry or humid periods). As a result we can observe differences between mean monthly values from subsequent years and an average from the seven-year period. It is also possible to detect differences in air humidity between the years in the same months, which may indicate the amount of precipitation which in turn can have an influence on the level of air pollution (Cichowicz et al. 2017).

Figures 6 and 7 shows the percentages of particular wind directions and the average wind speed in 2009–2015 based on 1-h data. The determined and marked SW and WSW directions

Table 3 Average humidity values [%] in particular months and years 2009–2015 (Monitoring Station Piotrkowice)

year month	2009	2010	2011	2012	2013	2014	2015	average
January	84,9	82,5	88,6	83,9	84,8	84,2	83,5	84,6
February	85,6	82,1	79,2	77,0	85,8	77,5	80,5	81,1
March	81,8	75,6	71,5	72,9	72,1	75,1	71,3	74,3
April	60,5	69,5	63,7	64,2	72,8	68,1	65,3	66,3
May	67,8	79,4	62,0	57,8	71,7	71,0	62,8	67,5
June	79,4	70,9	62,7	70,6	71,2	67,6	63,6	69,4
July	74,3	66,3	75,2	69,7	69,9	63,6	62,2	68,8
August	67,2	76,3	69,7	67,5	68,4	70,7	52,7	67,5
September	73,8	81,9	70,0	73,3	79,4	73,9	70,5	74,7
October	85,1	77,5	77,1	80,6	79,6	82,6	78,1	80,1
November	84,4	88,1	83,5	88,0	87,2	88,5	85,6	86,5
December	86,1	87,2	83,5	87,2	84,0	84,4	83,6	85,2

Fig. 6 Percentage of individual wind directions and average wind speed in 2009–2015 (Monitoring Station Piotrkowice)

Fig. 7 Wind rose for analyzed area (Monitoring Station Piotrkowice)

Fig. 7 (continued)

(violet color) result from the location of large industrial plants in these directions. The results of the percentage share of the wind direction were marked with vertical columns in green color and were defined in the legend as “direction” and also information about average wind speeds were given, denoting them with crosses in blue with the term “speed”.

The meteorological data presented in Tables 2 and 3 and in Figs. 6 and 7 relate to the Piotrkowice monitoring station.

In contrast, Fig. 8 presents the results of calculations of distributions for PM₁₀ suspended particulate matter in individual months depending on meteorological conditions, including wind speed. At the same time, the calculation has been referred to the acceptable level, which is 50 $\mu\text{g}/\text{m}^3$ and concerns the 24-h value. The calculations of the mean, maximum 24-h values from particular months of the seven-year period were made, and the average for each month was determined from them. In addition, the cases of exceedance of daily average values were also analyzed, as their permissible number during the year is 35. Very often it is a problem for particular cities/towns/villages.

Fig. 8 Concentration of PM10 of Monitoring Station Piotrkowice as a function of air temperature, humidity and wind speed in particular months of the year (Cichowicz et al. 2017) - data from the two-month winter period are marked in yellow and green color

The analysis confirmed (Fig. 8) that with low speeds of wind higher values of particulate matter PM10 were observed (data from the two-month winter period marked in yellow and green). However, when analyzing the data the twelve-month, it can be noticed that the general rule that at low wind speeds the most high concentrations of PM10 are observed not met. This is due to the proximity of the station from a large power plant, which in the summer (when there are mostly low wind speeds) works with less power emitting less pollution.

4 Conclusions

The effect of wind speed on air quality has been well-known and obvious (Boubel et al. 1994). It is well-known, that low wind speed promotes the formation of smog phenomena in cities. In the literature one can find many publications describing this phenomenon in relation to urban areas (Godish et al. 2015). This study, was decided to check whether such dependencies are also found in rural areas and whether the emission of pollutants from a large power plant affects the air pollution condition

registered at the measurement station and whether the observed concentrations are also changed in accordance with changes of meteorological conditions.

When analyzing the results, many situations are observed when higher PM₁₀ values appear at low wind speeds and vice versa, i.e. at higher wind speeds, the value of PM₁₀ is decreasing. This is due to larger “ventilation” of the air masses in the area considered and the displacement of pollutants over longer distances. On the other hand, elevated values of particulate matter PM₁₀ are a consequence of higher pollutant emissions during these periods (Figs. 4 and 5). The analysis also confirms the fluctuation (Figs. 3, 4 and 5) of PM₁₀ levels registered both by the station in Piotrkowice and obtained from the WIOŚ Poznań. When comparing the concentrations of suspended particulate matter PM₁₀ from both data sources, it can be observed that levels of this pollution recorded by the WIOŚ station in the periods of low wind speed were higher than the levels recorded in the Piotrkowice monitoring station. This may be related to the location of that station in the larger agglomeration and, therefore, higher emissions from car transport.

In conclusion, based on the data analyzed from the selected air quality monitoring station, it can be noted that in the analyzed period, the average PM₁₀ concentration level for the two-month winter period (i.e. December–January from 2009 to 2015) was 27.8 µg/m³ and was higher than the average level for 12 months - 25.7 µg/m³. These year-on-year concentrations changed irregularly, which does not allow unambiguous delineation of the trend line. As a consequence, it was noted that in the year-on-year analysis for the two-month period in 2010 and 2013 there were increases in PM₁₀ concentrations by 0.6% and 4.0% respectively, while in 2012 there was an increase by as much as 61.9% which resulted from the drop in the average concentration in 2011 by 57.6%, respectively. The drop in concentrations also occurred in 2015 by 29.1%. At the same time, a more regular trend for the average PM₁₀ concentration level for 12 months is noticeable, because in 2010, 2011, 2013 and 2015 they were respectively smaller year-on-year by 13.2%, 5.10%, 1.0% and 0.2%, while they increased in 2012 and 2014 by 4.6% and 1.6%, respectively.

Irregular changes registered in the winter period are most probably related to the winter temperature inversion, which is more and more often appearing in winter in Poland, lasting several times over a dozen or so days, which intensifies smog phenomena. The occurrence of dust smog in the vicinity of the monitoring station is the result of emission from emitters of small domestic furnaces, obsolete, fired with poor quality coal, where many of which are exploited in rural areas and small towns. The probable source of smog in this area is also intensive car transport.

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