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THE ANALYSIS OF AIR POLLUTION CAUSED BY PARTICLE MATTER EMISSION FROM THE COPPER SMELTER COMPLEX BOR (SERBIA)*

The main aim of this paper is to present the analyses of temporal variations of particulate matter in Bor (Serbia) influenced by the copper production at the Copper Smelter Complex Bor. Particulate emissions are of concern because the presence of fine particles ($PM_{2.5}$ - particles with diametar less than 2.5 μm) and ultrafine particles ($PM_{0.1}$ - particles with diametar less than 0.1 μm) assume higher risk for human health. Such particles can penetrate deeper into respiratory organs and, at the same time, a probability for such penetration and deposition in the respiratory system is greater. The analysis is based on the comparison of SO_2 and PM measurements at several locations in the area of Bor town in the close vicinity of Copper Smelter. PM concentrations were highly correlated with sulfur dioxide and inversely correlated with local wind speed during pollution episodes. The results presented indicate that the dominant source of coarse and fine particles in Bor town is the Copper Smelting Complex Bor. The most significant factors for particulate matter distribution are meteorological parameters of the wind speed and direction. It was found that the daily limit values exceed of concentrations of PM_{10} (50 μg/m^3) usually occurs due to very high concentrations in a period of several hours during the day.

Key words: sulfur dioxide; particulate matter (PM); respiratory particles; air pollution; monitoring.

The Municipality of Bor is located in a mountainous and forest area in the southeastern part of Serbia, close to the Bulgarian and Romanian borders (Figure 1). It has a total population of 65,000. The area has been the major centre for mining and processing of copper and other precious metals for almost a century. Air pollution is perceived as the main environmental problem in the Bor region. The main source of air pollution with SO_2 gas, heavy metals in PM and aero sediments is the Copper Smelter Plant within the RTB Bor Company (Copper Mining and Smelting Complex) which has been in operation for more than 100 years.

A typical pyrometallurgical copper smelting process includes four steps: roasting, smelting, concentrating, and fire refining. Ore concentrate is roasted to reduce impurities, including sulfur, antimony, arsenic, and lead. Smelting of roasted ore concentrate produces matte, a molten mixture of copper sulfide (Cu_2S), iron sulfide (FeS) and some heavy metals. By converting of matte, the high-grade “blister” copper of 98.5 to 99.5 % is recovered. Typically, blister copper is then fire-refined in an anode furnace, cast into “anodes”, and sent to the Electrolytic Refinery for further impurity elimination. Emissions from Copper Smelter are principally particulate matter and sulfur oxides (SO_x). Fugitive emissions are generated during material handling operations. Roasters, smelting furnaces, and converters are sources of both particulate matter and SO_x. Copper and iron oxides are the primary constituents of particulate matter, but other oxides, such as arsenic, antimony, cadmium, lead, mercury, and zinc, may be also present along with metallic sulfates and sulfuric acid mist. Fuel combustion products also contribute to the particulate emissions from multiple hearth roasters and reverberatory furnaces. Gas effluents from roasters are usually sent to the electrostatic precipitator (ESP) or spray cham-

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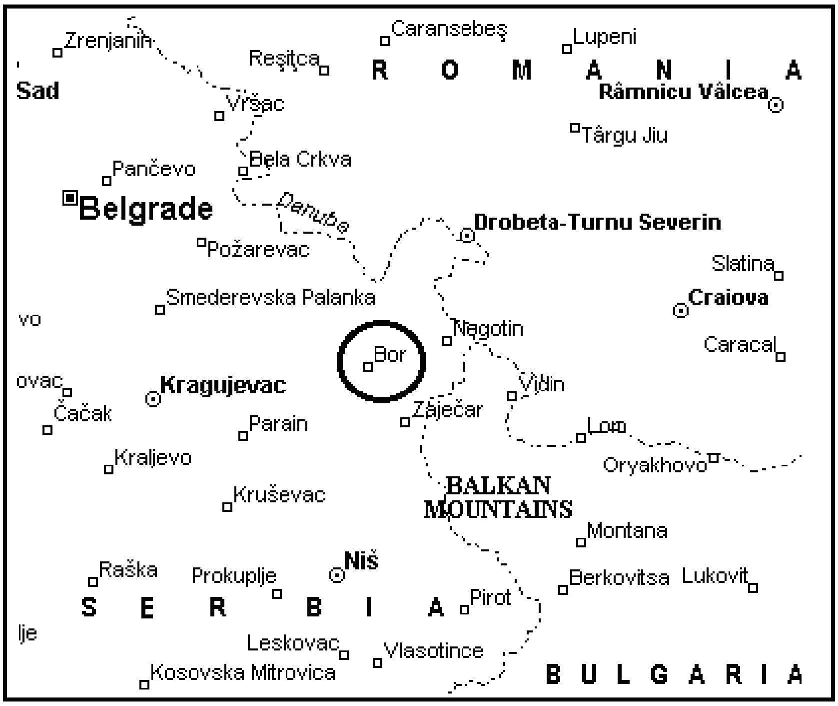

Figure 1. Map of eastern Serbia with the location of the Bor Municipality area.

ber/ESP system or combined with the smelter furnace gas effluent before particulate collection. Overall, the hot ESP system removes only 20 to 80% of total particulate present in gas. Cold ESP system may remove more than 95 % of total particulate. Particulate collection systems for smelting furnaces are similar to those for roasters. In the standard Pierce-Smith converter (like in the Copper Smelter Bor), the off-gases are treated in ESP system to remove particulate matter, and in the Sulfuric Acid Plant to remove SO_2. Control of SO_2 from the Smelter Plant is commonly performed in the Sulfuric Acid Plant.

The technology for the copper production in this Smelter Plant is outdated (classic pyrometallurgy with melting in furnaces and utilization of SO_2 gas in production of H_2SO_4 with relatively small degree of utilization <60%) which leads to the environmental pollution from higher concentrations of SO_2 and particulate matter [1] as well as aero sediments $PM > PM_{10}$. Ore melted in the Copper Smelter Plant in Bor is of chalcopyrite-pyrite type with the increased contents of arsenic which is found in the form of FeAsS and Cu_3AsS_4. The oxidation roasting and the melting of such mineral forms results in increased heavy metals oxides and SO_2 gas which, in certain quantities, contaminate the environment [2]. Reportedly, 170000 to 250000 t of SO_2 and 1300 t of particulate contaminated with heavy metals and up to 1000 t of arsenic, 500 t of lead, 2500 t of zinc and 1.6 t of mercury are emitted to the atmosphere each year [1,2].

In the Copper Smelter Plant in Bor there are two factory smokestacks (S1 and S2, as shown in Figure 2), the height of one is 120 m (D = 3 m) for the Smelter Plant off-gasses with contents up to 1% SO_2 and, the other of 150 m (D = 3.5 m) for gasses when the Sulfuric Acid Plant is out of operation (gases resulting from the roasting procedure in fluo-solid reactor mixed with converter gases) with SO_2 content of 5-6% in the gas. The parameters that characterize the emissions from the Copper Smelter are given in Table 1. On average, the Sulfuric Acid Plant is out of operation for about 3-6 months in a year. As a consequence, a large amount of sulfur dioxide is discharged directly into the atmosphere, together with toxic metals [2]. Both smokestacks are situated in the immediate vicinity of the urban settlement at a distance less than 500 m from the old urban center with numerous vital functions of the town. In addition, airborne dust resulting from the Open Pits and surrounding waste heaps which contain heavy metals, contributes to the air pollution of the area. Taking into account the location of the industrial complex and dominant wind directions, these pollutants are spread over the Bor town and the surrounding area. Therefore, the inhabitants of the Bor town are exposed to high levels of air pollution, which can pose serious risks to their health [3-6].

SO_2 is one of the most important pollutant of the environment and mostly originates from the oxidation of sulfur compounds. Anthropogenic emission of SO_2

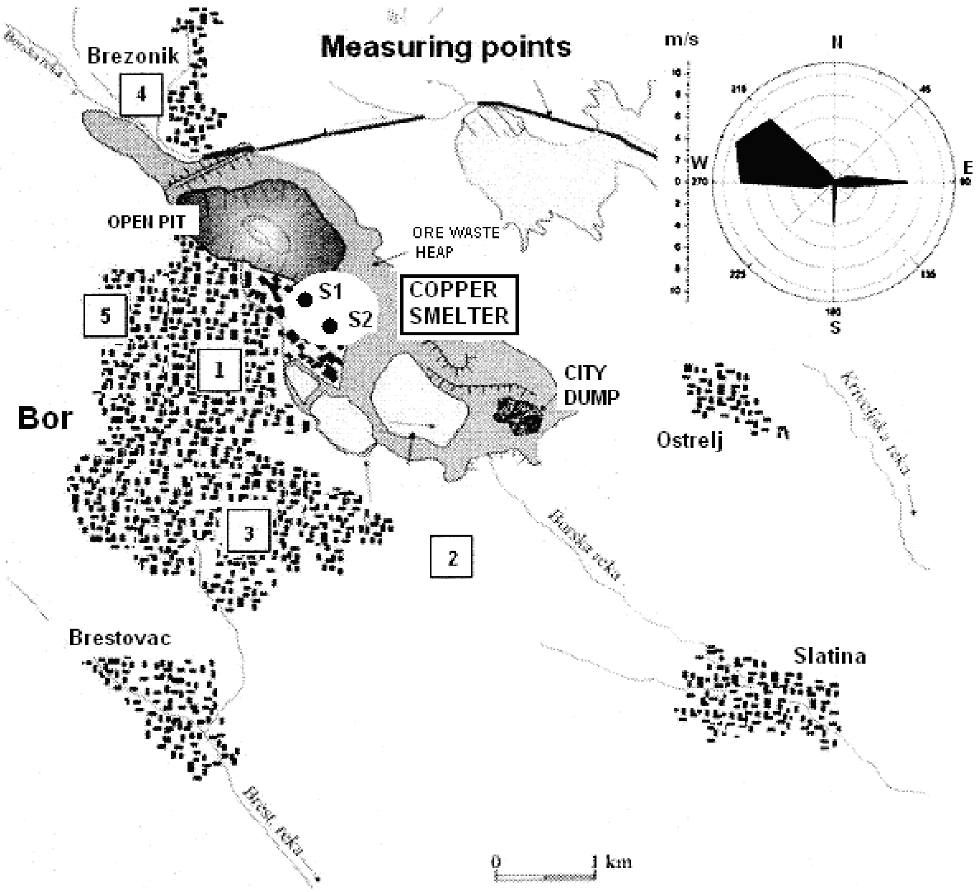

Figure 2. Map of the Bor Municipality area with measuring points (1. Park; 2. Jugopetrol; 3. Institute; 4. Brezonik; 5. Hospital) and location of the Copper Smelter smokestacks (S1, S2).

results from burning the fossil fuels (coal and heavy oils) or smelting of sulfide ore concentrates (most frequently Cu, Pb, and Zn ores). SO_2 is an irritant gas which causes breathing problems when people are exposed to its high concentrations. Although sulfur is useful for plants in small concentrations, the atmosphere pollution with SO_2 gas negatively affects plants due to its higher concentrations and the impact size depends on its concentration. Smoke and particulate are nearly always associated with SO_2 and can cause difficulties in data interpretation and health risk assessments. Therefore, there is uncertainty associated with long-term (24 h plus) epidemiological studies. There is a possibility that the adverse effects of sulfur dioxide are really the effects of particulate or other associated substances. Due to the certain negative effect of SO_2 in the atmosphere, European Union limits its mass contents: the limit per hour for the protection of human health is 350 μg/m^3, not to be exceeded more than 24 times per calendar year; a daily limit for the protection of human health is 125 μg/m^3, not to be exceeded more than three times per calendar year; and the annual limit for the protection of ecosystems is 20 μg/m^3 [7,8].

Suspended particles are one of the most important ambient air polluters which adversely affect human health. Prolonged exposure to PM particles often cause respiratory and cardiovascular diseases and increase mortality [3-6]. For the purpose of the protection of human health EU has introduced two limi-

Table 1. Parameters that characterize the off-gases emissions from the Copper Smelter Plant

Smokestack S1			Smokestack S2		
Parameter	Min	Max	Parameter	Min	Max
Gas flow, m^3/h	90000	180000	Gas flow, m^3/h	0	300000
SO_2 content, %	0.1	0.9	SO_2 content, %	0.5	8
Temperature, °C	150	300	Temperature, °C	100	300
Dust content, g/m^3	0.3	3	Dust content, g/m^3	0.05	0.8

tations for PM_{10} which should be implemented in two periods: the first one at the beginning of 2005 and the second one in 2010. The limit values for 2005 and 2010 are as follows: a daily limit of 50 μg/m^3 not to be exceeded more than 35 times per calendar year and the annual limit of 40 μg/m^3. The limits, which will be implemented after the year 2010, are: a daily limit of 50 μg/m^3, not to be exceeded more than seven times per calendar year and the annual limit of 20 μg/m^3 [7,8].

Sampling sites

In the Mining and Metallurgy Institute Bor, Department for Chemical and Technical Control (CTC), there is a group for measuring the meteorology parameters and the air quality control. The results presented in this paper cover some experimental programs performed by CTC during 2004-2009 at 5 locations (locations 1-5 in Figure 2).

The monitoring of sulfur dioxide, particulate, and toxic metals has been carried out for many years in Bor. However, the methods and equipment are old and do not fully comply with the modern requirements for monitoring the atmospheric pollution. Since the beginning of 2004, the new, suitable atmospheric monitoring equipment has been put into operation. The equipment, used during the experimental programs, consists of three fixed stations for measuring the ambient sulfur dioxide concentrations, one mobile station and two fixed stations for measuring the ambient particulate (PM). The fixed stations were installed close to the Copper Smelter Complex in positions downwind from two prevailing wind directions (measuring points Park, Jugopetrol and Brezonik, as shown in Figure 2).

The prevailing winds are from west-northwest and therefore tend to carry away the pollution from the main population centers (the wind rose diagram in the time interval from 1998 to 2008 is also shown in Figure 2). During rainy periods, typical east or southeast winds are of more concern. Low or zero wind conditions occur regularly (more than 50% of time). Light and variable winds are likely to cause very high localized concentrations of pollutants.

Distances between measuring points and Copper Smelter Plant smokestacks are given in Table 2.

Measuring point 1 Park – fixed station was placed downwind of the easterly prevailing wind. This location is within the Central Park in Bor. The site is located 650 m west from the Copper Smelter Plant. A dense population (mainly high-rise) is directly downwind from the Copper Smelter Plant during east winds. A large effect on the local environment is often noted at this location – burning eyes, throat, the taste of sulfur dioxide is experienced. This station is also equipped with meteorological instrumentation.

Measuring point 2 Jugopetrol – fixed station was placed downwind of northwesterly prevailing wind. The site is located 2 km south/southeast from the Copper Smelter Plant downwind during northwesterly winds. In the vicinity of the measuring point (1 km northeast) is the city dump. Although, the site appears to be in an area of low population density, some small villages are nearby (Ostrelj, Slatina, Brestovac), so there is an affected population.

Measuring point 3 Institute – fixed station was placed downwind of northeasterly prevailing wind. The site is located about 2 km south/southwest from the Copper Smelter Plant downwind during northeasterly winds. In the vicinity of the measuring point is Foundry Castings of copper alloys with the device for sanding. The dense population is directly downwind from the Copper Smelter Plant during northeasterly prevailing winds. This station is also equipped with meteorological instrumentation.

Measuring point 4 Brezonik – fixed station was placed downwind of southeasterly prevailing wind. The site is located about 2 km north/northwest from the Copper Smelter Plant downwind during southeasterly winds. In the vicinity of the measuring point is the Open Pit. Although the site appears to be in the area of low population density, some small villages are nearby (Veliki Krivelj, Brezonik) so there is the affected population.

Measuring point 5 Hospital – fixed station was placed downwind of easterly prevailing wind. This location is within the town hospital. The site is located 1

Table 2. Distances between measuring points and Copper Smelter Plant smokestacks S1 and S2

No.	Measuring location	Altitude, m	Distances from smokestacks S1 and S2, m	
			R1	R2
1	Park	370	650	650
2	Jugopetrol	382	2500	2500
3	Institute	386	2142	2032
4	Brezonik	400	2000	2000
5	Hospital	408	1000	1180

km west from the Copper Smelter Plant. The dense population (mainly high-rise) is directly downwind from the Copper Smelter Plant during east winds. A large effect on the local environment is often noted at this location – burning eyes, throat, taste of sulfur dioxide is experienced.

EXPERIMENTAL

The automatic measuring stations for real-time determination of SO_2 concentration have been installed at three measuring points (points 1, 2 and 4 in Figure 2). These instruments provide continuous and reliable measurement of SO_2 in ambient air. Data transfer from measuring stations to the control center in Mining and Metallurgy Institute Bor is carried out every 15 min. The content of SO_2 in the air is determined by UV-fluorescence after excitation to higher energy level and light emission measurement. This method enables automatic determination of SO_2 contents in ambient air according to ISO 10498 Standard. The reference method for sulfur dioxide measurement is described in EN 14212:2005 "Ambient air quality - Standard method for measurement the sulfur dioxide concentration by ultraviolet fluorescence" [8]. Using UV-fluorescence method, the analyzers perform automatic measuring of SO_2 in ambient air in the concentration range from 0 to 10000 μg/m^3 with linearity of ±1% and minimum detectable limit (2σ) of 0.001 ppm (<3 μg/m^3). The analyzers were calibrated with standard gas mixtures (200 ppb) from certificated gas cylinders at least once in every three weeks. The calibration gas mixtures in cylinders are checked every year by an independent audit.

At two measuring points (points 2 and 5 in Figure 2) the measurements were carried out using the standard UK 8-port samplers. Sulfur dioxide is measured by air passing through a dilute-acid solution of hydrogen peroxide (classical acidimetric method [9--12]). Sulfur dioxide reacts with hydrogen peroxide to form sulfuric acid which is titrated with a standard alkaline solution, and sulfur dioxide concentration is calculated using the standard calculation (British Standard 1747 and ISO 9835 are reference documents for this technique). The limit of detection for the technique is less than 0.01 ppm. The results are comparable with those obtained by measurements of automatic analyzers carried out in parallel [13].

The reference method for sampling and measurement of PM_{10} is described in EN 12341:1999 "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". The reference method for the sampling and measurement of $PM_{2.5}$ is described in EN 14907:2005 "Standard gravimetric measurement method for determination of $PM_{2,5}$ mass fraction of suspended particulate matter".

The concentrations of particulate matter presented in this paper were monitored using portable, direct reading, airborne particle analyzers Osiris (at measuring points 1, 2, 3 and 5 during 2004-2006) and Grimm EDM180 (at measuring point 1 during 2009). These devices were designed for simultaneous real time measurement of *PM* (PM_{10}, $PM_{2.5}$ and PM_1) according to the European Standards EN 12341 (for PM_{10}), and EN 14907 (for $PM_{2.5}$). Detection limit (2σ) for technique is less than 0.1 μg/m^3 within a particle size range (diameter) between 0.5 to 20 μm. PM_1 values were also reported, although no EN standard currently exists. Also, the concentrations for PM_{10} are monitored using BAM1020 ambient particulate concentrations analyzer (measuring point 4 during 2007-2008). This analyzer is using beta ray attenuation method according to the U.S. EPA Designations PM_{10}: FEM (EQPM-0798-122), $PM_{2.5}$: Class III FEM, (EQPM--0308-170) with lower detection limit (2σ) less than 4.0 μg/m^3 and standard range between 0 to 1000 μg/m^3.

All analyzers have a possibility of automatic calibration (zero), a definition of arbitrary interval sampling, averaging and saving the measured values, as with the local keyboard, and indirectly through the remote supervisory computer. The monitoring data from real time monitors have been available originally based on 15-min averages. In order to provide necessary working conditions, the analyzers are placed within a closed container that is air-conditioned (18 to 20 °C) and has a stable power supply. The analyzers operate in accordance with the manual for the equipment. Maintenance schedules for replacement of consumable parts, diagnostic checks and equipment fully follow the manufacturer recommendations. Routine and non-routine service visits are documented with detailed descriptions as well as the results of analyzer tests or calibrations performed during monitoring programs. Data validation was followed by checking in three-month intervals to ensure that they are reliable and consistent. For calculation of daily averages, minimum 80% of 15-min averages were required; otherwise, the value was considered as missing. Any suspicious data in the original "row" data set, such as large spikes or spurious high concentrations were fully investigated. Hourly and daily averages, used for statistical considerations, were calculated from 15-min averages. Sulfur dioxide and *PM* mass concentrations divided into annual, winter (October-March) and summer (April-September) averages are gathered in Table 3.

RESULTS AND DISCUSSION

The emissions from the Copper Smelter are principally particulate matter and sulfur oxides. As it was mentioned, smoke and particulate are nearly always associated with SO_2 and can cause difficulties in data interpretation. Measurements of concentration of sulfur dioxide and respiratory particles were carried out in the times when the Copper Smelter was in operation, as well as in the times when the Copper Smelter did not work continuously. Typical time series with mass concentrations of SO_2 and PM_{10} during the time when the Copper Smelter was out of operation are presented in Figure 3 (measuring point 1 Park). Typical time series with mass concentrations of SO_2 and PM_{10} during the time when the Copper Smelter was in operation were presented in Figures 4–6 (measuring points 1, 5 and 4, respectively).

Strong fluctuations of daily average mass concentrations can be observed. Especially SO_2 and PM_{10} were characterized by strong amplitudes mostly related to changes in weather (wind speed and direction) conditions. This phenomenon is typical in conditions with the wind speed less than 2 m/s and such wind direction that air pollution can be detected at the measuring points (as shown in Figures 3-5). Excursions over daily limit values of concentrations of SO_2 and PM_{10} usually occurred due to very high concentrations in a period of several hours during the day (as shown in Figure 4).

According to the data present in Table 3, annual

Table 3. Average daily concentration, standard deviation (SD) and ranges of SO_2, PM_{10}, $PM_{2.5}$ and PM_1 ($\mu g\ m^{-3}$) at selected measuring locations during measuring periods

Measuring location	SO_2		PM_{10}		$PM_{2.5}$		PM_1	
	Mean (*SD*)	Max/Min	Mean (*SD*)	Max/Min	Mean (*SD*)	Max/Min	Mean (*SD*)	Max/Min
1. Park								
Year (2004)	86 (78)	914/11	41.1 (39.2)	204.5/2.8	22.7 (24.2)	123.7/1.4	9.6 (9.7)	89.8/0.6
Winter (2004)	68 (48)	892/11	40.7 (41.6)	204.5/2.8	23.0 (23.4)	88.9/1.4	9.9 (9.3)	36.6/0.6
Summer (2004)	103 (102)	914/11	36.6 (37.0)	138.1/12.5	22.4 (34.2)	123.7/7.7	7.5 (27.6)	89.8/2.9
Year (2006)	227 (292)	2441/10	32.7 (36.4)	204.3/1.9	14.0 (14.6)	68.5/1.2	5.7 (5.7)	27.2/0.4
Winter (2006)	255 (355)	2441/14	32.6 (47.5)	204.3/1.9	16.1 (18.1)	68.5/1.2	6.8 (7.0)	27.2/0.4
Summer (2006)	209 (246)	1370/10	41.7 (15.1)	77.7/17.7	10.6 (4.3)	49.3/4.6	3.5 (1.6)	6.9/1.0
Year (2009)	112 (157)	777/3	32.4 (16.3)	111.5/3.0	23.7 (13.5)	96.5/3.0		
Witer (2009)	160 (182)	777/4	36.1 (20.7)	111.5/3.0	29.2 (17.8)	96.5/3.0		
Summer (2009)	108 (128)	492/3	30.2 (12.5)	65.7/10.0	20.3 (8.3)	54.0/4.0		
2. Jugopetrol								
Year (2006)	178 (168)	1081/10	44.1 (29.4)	136.3/5.5	19.1 (17.7)	83.3/2.5	6.9 (7.3)	36.5/0.9
Winter (2006)	151 (150)	759/10	37.5 (28.4)	108.1/5.5	19.8 (22.6)	83.3/2.5	8.3 (10.3)	36.5/0.9
Summer (2006)	194 (177)	1081/10	48.5 (30.5)	136.3/14.4	19.4 (15.4)	62.7/4.0	6.3 (5.2)	23.3/1.1
3. Institute								
Year (2006)	62 (70)	589/10	38.3 (21.7)	116.7/9.8	16.0 (8.1)	49.3/2.0	6.7 (6.2)	22.9/0.9
Winter (2006)	66 (91)	589/10	37.3 (16.0)	72.7/9.8	19.5 (8.1)	49.3/2.0	9.7 (5.9)	22.9/1.9
Summer (2006)	59 (57)	422/10	39.4 (26.7)	116.7/12.5	10.3 (4.4)	46.2/3.3	3.6 (4.9)	21.2/0.9
4. Brezonik								
Year (2007)	44 (61)	328/5	42.5 (32.6)	293.6/8.8				
Winter (2007)	43 (64)	328/11	53.2 (41.5)	293.6/8.8				
Summer (2007)	45 (59)	217/5	32.4 (15.9)	111.0/10.3				
Year (2008)	68 (144)	1642/10	45.7 (29.9)	188.3/11				
Winter (2008)	92 (199)	1642/10	52.8 (34.9)	188.3/11				
Summer (2008)	45 (35)	196/10	35.2 (15.3)	84.9/14.7				
5. Hospital								
Year (2006)	228 (248)	1291/10	53.0 (66.5)	393.7/10	17.8 (18.7)	101.8/2.7	6.6 (7.1)	41.3/1.1
Winter (2006)	255 (290)	1291/14	34.2 (16.6)	73.5/12.7	14.2 (7.5)	30.1/3.8	6.0 (3.6)	14.1/1.3
Summer (2006)	210 (214)	843/10	65.9 (83.7)	393.7/10	20.2 (23.4)	101.8/2.7	7.0 (8.8)	41.3/1.1

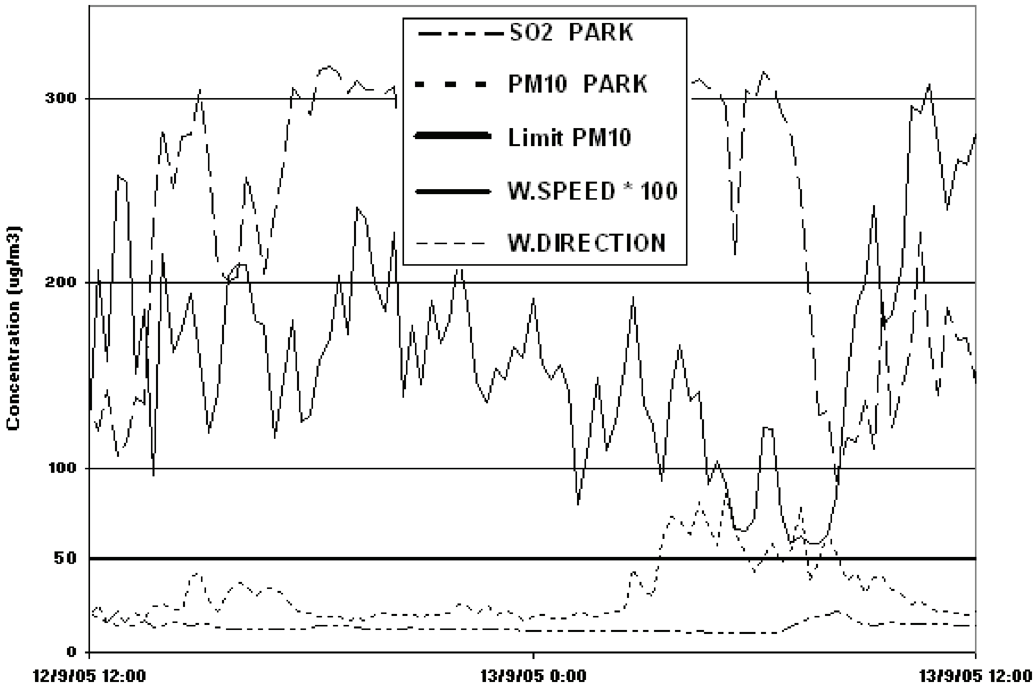

Figure 3. Time series of SO_2 and PM_{10} mass concentrations at measuring point 1 (Park) in the time interval when the Copper Smelter Bor was out of operation.

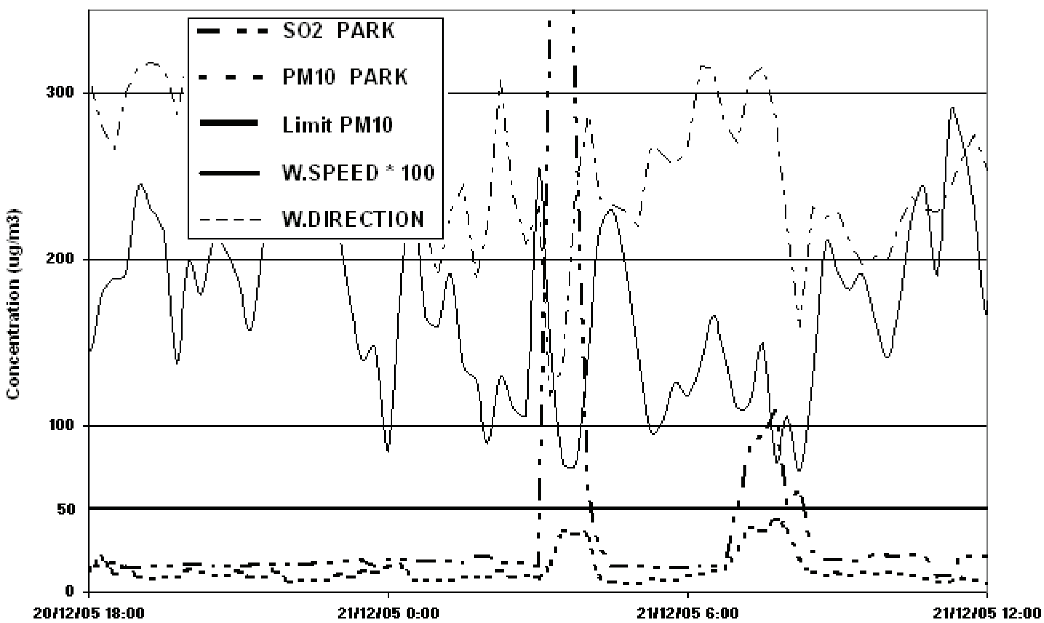

Figure 4. Time series of SO_2 and PM_{10} mass concentrations at measuring point 1 (Park) in the time interval when the Copper Smelter Bor was in operation.

average values range form 44 to 228 μg/m^3 for SO_2, 32.7 to 53.0 μg/m^3 for PM_{10}, 14.0 to 23.7 μg/m^3 for $PM_{2.5}$ and 5.7 to 9.6 μg/m^3 for PM_1. Variation of daily means can be demonstrated by variation coefficients, *i.e.*, the standard deviation divided by the mean. The variability of SO_2 mass concentrations at measuring locations is very different, between 91 and 212%. The variability of *PM* mass concentrations at measuring locations changes between 57 and 125% for PM_{10}, between 51 and 105% for $PM_{2.5}$ and between 72 and 108% for PM_1.

Based on comparisons of these results with the data of sulfuric acid and the copper cathodes production shown in Table 4, we made a conclusion that

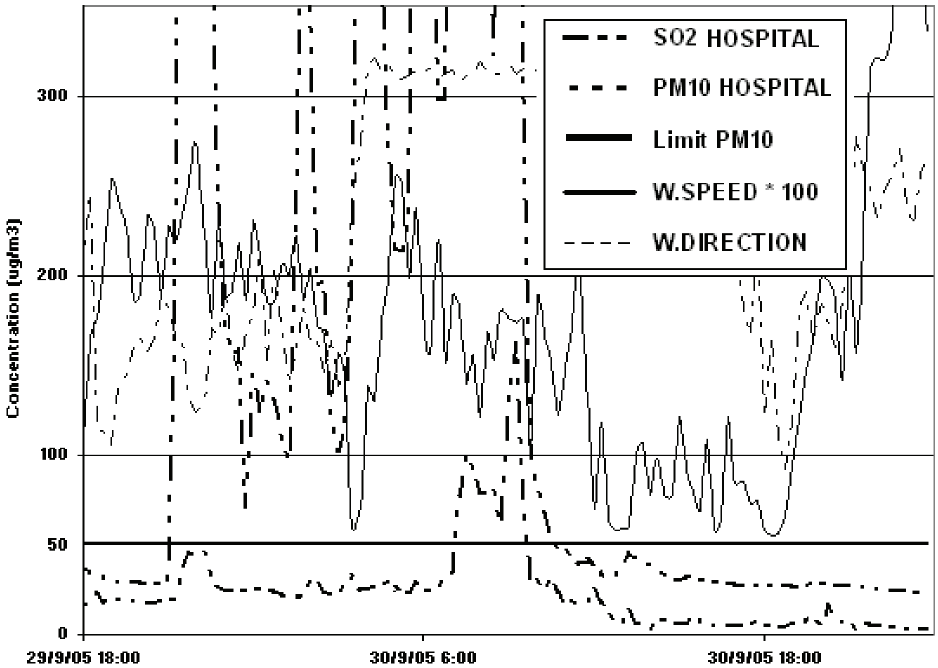

Figure 5. Time series of SO_2 and PM_{10} mass concentrations at measuring point 5 (Hospital) in the time interval when the Copper Smelter Bor was in operation.

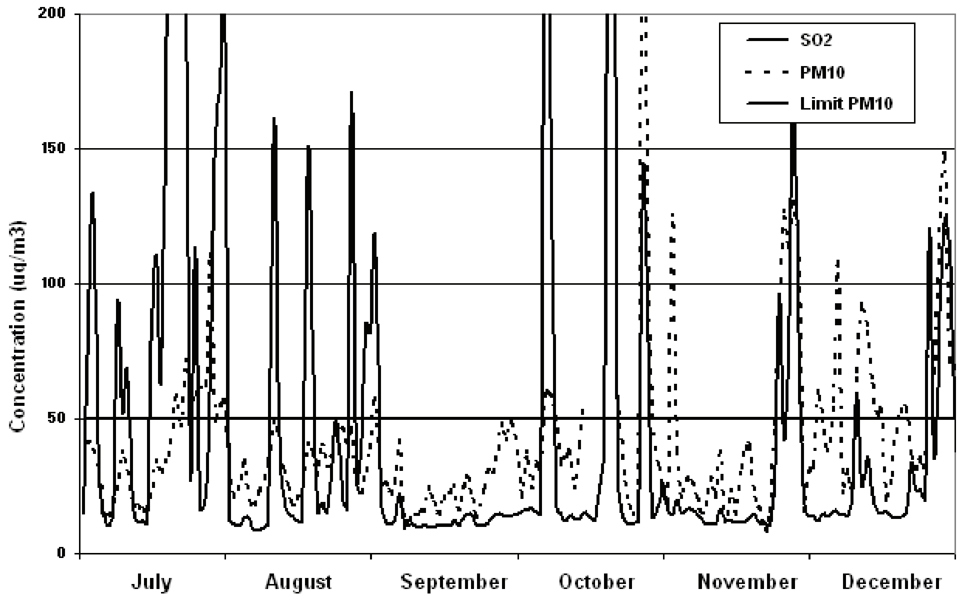

Figure 6. Time series of SO_2 and PM_{10} mass concentrations at measuring point 4 (Brezonik) during 2007 in the time interval when the Copper Smelter Bor was in operation.

emissions of these pollutants from the Copper Smelter Bor were the dominant cause of the air pollution episodes at almost all measuring points. However, the concentrations of SO_2 were clearly higher at locations 1, 2 and 5 compared to concentrations at locations 3 and 4. This can be explained by the fact that these measuring points are of the dominant wind direction relative to the Copper Smelter. Also, measuring points 1 and 5 are at half the distance from the Copper Smelter smokestacks relative to other measuring points and the values of SO_2 concentration at these measuring points are expected to be higher. The average annual concentrations of SO_2 measured at measuring points 1, 2, and 5 are the largest in the Republic of Serbia. These values are at least two times higher than those measured in Kostolac and Belgrade for the last few years.

The average annual concentrations of PM_{10} measured in Bor (32.7 to 53.0 μg/m^3) appear to be at the same level of PM_{10} concentrations measured in 2001 in selected European cities [14], or even lower [15, 16]. The average annual concentrations of PM_{10} were slightly higher at measuring points 2, 4 and 5 compared to the concentrations at measuring points 1 and 3. At measuring points 4 and 5, major seasonal changes in concentrations of PM_{10} can be detected relative to other measuring points. The concentrations of PM_1 were very similar at all locations.

Table 4. Production of sulfuric acid and copper cathodes in the Copper Smelter Plant (2004-2008)

Year	H_2SO_4 production, t	Cu production, t
2004	49100	12000
2005	92900	21000
2006	71500	41000
2007	66500	31000
2008	70800	34000

The changes in SO_2 and PM_{10} concentrations at measuring point 1 (Park) were simultaneous during the almost whole periods of SO_2 pollution episodes when the Copper Smelter Bor was in operation (as shown in Figure 4). The same conclusion can be made for changes of PM_{10}, $PM_{2.5}$ and PM_1 concentrations. Very little difference was found between the average concentrations for the summer and winter seasons. These results imply that the area in the vicinity of the measuring point 1 is influenced by the same source of pollution, that is the Copper Smelter Bor.

The changes in SO_2 and PM_{10} concentrations at measuring point 2 (Jugopetrol) were simultaneous during almost the whole measuring period. This measuring point is more than 2 km away from the Metallurgy Complex, so the influence of other sources of pollution (such as the city dump and ore waste heap) in some periods is dominant. The same conclusion can be made for mass concentrations of $PM_{2.5}$ and PM_1.

The changes in SO_2 and PM_{10} concentrations at measuring point 3 (Institute) are not so simultaneous as at measuring points 1 and 2. Anomalies can be frequently seen in the second half of the year. Very little difference was found between the average concentrations for the summer and winter seasons. This measuring point is not on the dominant direction of the wind from the Metallurgy Complex, which is the main source of SO_2 and particulate pollution, so the influence of other sources of pollution (such as traffic or Foundry Castings) in these periods is dominant. Mass concentrations of PM_{10}, $PM_{2.5}$ and PM_1 have a similar trend.

The changes in SO_2 and PM_{10} concentrations at measuring point 4 (Brezonik) do not have the same trend during the year, the trend is even inverted in some periods. This measuring point is not on the dominant direction of the wind from the Metallurgy Complex, so the influence of other pollution sources (such as traffic, ore waste heap or individual fireplaces) in these periods is dominant. This measuring point expressed strong influence on individual fireplace usage during the winter period so that in this period the measured concentrations were higher than those during the summer (relative change in PM_{10} concentrations of 39% during 2007, and 33% during 2008). Nevertheless, the influence of the Metallurgy Complex on air pollution at this measuring point should not be neglected, since it is dominant in some periods.

The changes in SO_2 and PM_{10} concentrations at measuring point 5 (Hospital) are proportional during the whole measuring period when the Copper Smelter Bor is in operation (as shown in Figure 5). The same conclusion can be made for mass concentrations of PM_{10}, $PM_{2.5}$ and PM_1. The geographical position of this measuring point is such that, in winter, the winds that mostly blow from the north/northwest contribute to the reduction of PM pollution relative to the summer period when the frequency of winds from these directions is lower (relative change in PM_{10} of 48%, in $PM_{2.5}$ of 30% and in PM_1 concentrations of 14% during 2006). This measuring point is in the vicinity of the Copper Smelter Bor, hence it is the dominant source of air pollution.

CONCLUSIONS

Monitoring of mass concentrations of PM is very important from the aspect of risk assessment to human health. Measurements of concentration of *PM* (PM_{10}, $PM_{2.5}$ and PM_1) at the measuring sites in the urban area of Bor lead to the following conclusions:

- Presented results indicate that the dominant source of coarse particles in Bor town is the Copper Smelting Plant Bor. The most significant factors for the distribution of pollutants are meteorological parameters of wind speed and direction.

- Exceeding of daily limit values of PM_{10} concentrations (50 μg/m^3) usually occur due to very high concentrations in the period of several hours during the day. This is in good correlation with the detected values of SO_2 concentrations. Therefore, while most of the particle pollution is below the limit value, a large pollution intensity for a few hours, one or more times during the day, can lead to an exceedance of the daily average limit value.

- The share of PM_{10} particles in TSP (total suspended particles) is generally more than 70%, so that a PM_{10} level exceeding the limit value is usually observed when the TSP pollution is above its limit value.

Very extensive research is ongoing in order to correlate *PM* results with meteorological parameters and find relationships among *PM* and other pollutants. Further work in this area should focus on prediction of sulfur dioxide and particles concentrations in real time, in order to provide short-term forecast of air quality.

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NAUČNI RAD

ANALIZA ZAGAĐENJA VAZDUHA USLED EMISIJE LEBDEĆIH ČESTICA IZ TOPIONICE BAKRA U BORU (SRBIJA)

Cilj rada je analiza promena koncentracija lebdećih čestica u široj oblasti grada Bora pod uticajem emisije ovih čestica iz rudarsko metalurškog kombinata RTB Bor. Kvantitativna i kvalitativna analiza lebdećih čestica, posebno finih ($PM_{2.5}$ - čestice prečnika manjeg od 2.5 μm) i ultrafinih ($PM_{0.1}$ - čestice prečnika manjeg od 0.1 μm) od izuzetnog je značaja zbog njihovog negativnog uticaja na ljudsko zdravlje. Fine i ultrafine čestice mogu da prodru dublje u respiratorne organe, pri čemu je zahvaljujući njihovim dimenzijama i verovatnoća za takav prodor i taloženje u respiratornom sistemu veća. U radu je prikazano poređenje koncentracija SO_2 i lebdećih čestica na nekoliko lokacija u Boru u blizini Topionice bakra. Izmerene koncentracije lebdećih čestica u jakoj su direktnoj korelaciji sa izmerenim koncentracijama sumpor dioksida, dok su u negativnoj korelaciji sa brzinom vetra u vreme epizoda aerozagađenja. Prikazani rezultati ukazuju na to da je na širem gradskom području Bora najvažniji izvor čestičnog zagađenja rudarsko metalurški kombinat RTB Bor. U radu je pokazano da na rasprostiranje lebdećih čestica najviše utiču meteorološki parametri brzina i pravac vetra. Takođe, ustanovljeno je da prekoračenje graničnih vrednosti (srednje dnevne koncentracije) PM_{10} (50 $\mu g/m^3$) najčešće dolazi usled epizoda zagađenja. Do pojava veoma visokih koncentracija lebdećih čestica dolazi jednom ili više puta u toku dana u zavisnosti od aktivnosti u metalurškom kombinatu RTB Bor i opštih meteoroloških uslova.

Ključne reči: sumpor-dioksid; lebdeće čestice (PM); respiratorne čestice; zagađenje vazduha; monitoring.