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Decreasing Solid Aerosols from Small Heat Sources Using the Optimized Electrostatic Precipitator

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Abstract: Air quality and air pollution are important issues, and thus it is necessary to look at possibilities for how to decrease emissions in the atmosphere affordably and effectively. This article focuses on solid aerosols, specifically particulate matter, and the design of a low-cost solution for their decrease in the atmosphere. The mass concentration of particulate matter with the proposed optimized electrostatic precipitator was measured and compared with measurement without its implementation. Based on the results, it can be concluded that the designed ESP type could catch approximately 71% of solid particles. However, the real ability to capture particulate matter could be expected to be approximately 50–60% due to possible clogging, irregular cleaning and maintenance under normal conditions. Further, the article deals with the application of the village model with this type of electrostatic precipitator in households. Based on this model, the production of particulate matter would be reduced from 12.24 t/year to 6.12 t/year considering 50% separation efficiency and to 5.25 t/year considering 60% separation efficiency by the application to all heat sources for burning solid fuels for all emission classes. However, the reduction in particulate matter would be lower in real conditions.

Keywords: particulate matter; electrostatic precipitator; reducing emissions; solid aerosols

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1. Introduction

An important priority of the European Union is the improvement of air quality. Air pollution has a negative impact on the health of the human population, especially in areas of large cities [1]. The report Air Quality in Europe 2021 states that despite an increase in gross domestic production, emissions of all major air pollutants in the EU-27 have continued to decline from 2005 to 2019. The main sources of PM10 (particulate matter smaller than 10 µm) and PM2.5 (particulate matter smaller than 2.5 µm) were residential, commercial and institutional energy consumption, responsible for 40% and 53% of emissions, respectively. Other pollution sources were road transport, manufacturing and extractive industry and even agriculture for PM10. However, the concentrations of PM10 and PM2.5 have decreased by 27% (PM10) and 29% (PM2.5) since 2005 [2].

According to the Slovak Hydrometeorological Institute, the largest sources of PM (particulate matter) in Slovakia in 2019 were households (62.1% for PM10, 79% for PM2.5), followed by traffic (8.3% for PM10, 8.0% for PM2.5), energy (7.7% for PM10, 6.1% for PM2.5), industry (8.2% for PM10, 4.6% for PM2.5), agriculture (13% for PM10, 1.4% for PM2.5) and waste (0.7% for PM10, 0.9% for PM2.5). Compared to 2005, there was a significant decrease in the production of particulate matter (about 18.28 kt for PM10 and about 20.85 kt for PM2.5). However, there was a slight increase compared to 2018 (about 0.44 kt for PM10 and about 0.62 kt for PM2.5), probably as a result of legislative and technological progress, a change in the fuel base, industrial production, etc. [3]. These conclusions are in accordance with the air quality management strategy for the city of Žilina, including the functional

urban area for the period 2020 to 2040. In 2015, 1% of the population of Žilina lived in an area where the PM10 exceeded the permitted limit. This represents an improvement over 2006 and 2010, where it was 73% of the city's population (2006) and 10% of the population (2010). The same was the case with PM2.5, where 51% of Žilina residents lived in an area where the annual limit for PM2.5 was exceeded in 2015. In 2006 and 2010, it was 86% of the city's residents (2006) and 81% of the population (2010). Households are also the greatest sources of PM production in the Žilina region, followed by traffic and industrial sources such as paper mills, cement mills, lime production and ferroalloys [4].

Pospisil et al. dealt with the dispersion characteristic of PM10 near roads in urban areas. The character of the air velocity field mainly affected this dispersion [5]. Furthermore, the secondary formation of aerosols by processes such as conversion and condensation caused other nanoparticle formations in urban regions. However, the pollutants are closer to the Earth's surface during winter, which is caused by the lower height of the planetary boundary layer due to colder temperatures and higher air density, which is caused by winter inversion [6]. Therefore, it is important still to look at possibilities for how to decrease solid aerosols and other emissions in the atmosphere that will be both affordable and effective.

Possible solutions for households can be using modern ecologic heat sources or lower-cost solutions such as secondary separators for solid particles, placed in the chimney pipe behind the heat sources. In general, the most common types of separators are filters and mechanical and electrostatic separators. The electrostatic precipitators (ESPs) have achieved the highest efficiency for the particle spectrum 0.01 μm–1000 μm. These separators can differ by the number of stages or the geometric configuration. The research of Trnka et al. has already compared the single-pipe electrostatic chimney precipitator with the four-pipe type. The results showed the separation efficiency increased from 66% to 85% [7]. The design of a low-cost ESP was the aim of the research of Drga et al. They observed the impact of increasing the area of electrodes by dividing precipitation space and also increasing the number of charging electrodes. The results confirmed the suitability of the observed ESP type [8]. Dong et al. investigated the charging and transport of fine particles based on wire–plate electrostatic precipitators with multiple wire electrodes. The authors found an improvement in efficiency upon increasing the high voltage range and the wire spacing. The changing of the discharge-electrode arrangement showed a much greater effect on the charging and transport particle behavior in the model of M3, which had the highest trapping efficiency [9]. Schmatloch and Rauch improved the shape of the electrode and achieved a collection efficiency of about 90% based on the particle number, while their solution should be compact and inexpensive [10]. Schittl et al. pointed out the difficult implementation of modern downstream ESP in the smaller furnaces due to economic and space aspects. Their solution dealt with the integration of ESP systems into the heat exchanger of a small-scale furnace for biomass. The results showed that the separated particles PM10 could be over 50% during full load and even over 80% during part load [11]. Nussbaumer and Lauber monitored the ESP availability of seven heating plats with tube-type and plate-type electrostatic precipitators. Their results showed that the ESP availabilities could be greater than 90%. However, the main source of low availabilities were malfunctions and maintenance problems without their reparation. Still, an availability greater than 95% could be reached for new plants [12]. Dastoori et al. dealt with the particle trajectory in a chimney pipe with an electrostatic precipitator consisting of a central electrode and outer electrode, while the central electrode was connected to high voltage. One of the most important factors has been the gas flow rate [13]. Jaworek et al. compared the collection efficiency of a two-field electrostatic precipitator with a two-stage electrostatic precipitator comprising an electrostatic agglomerator. The mass collection efficiency was similar, but the power consumption of the electrostatic agglomerator was 10–50 times lower [14]. Zhu et al. developed an integrated two-stage type of ESP for PM2.5 removal based on air purification. Their solution could reach a collection efficiency of up to 99% at 3 $m.s^{-1}$ gas velocity [15].

Based on this knowledge, it is important to optimize and implement electrostatic precipitators or other lower-cost separators with the aim of environmental protection and decreasing emissions. This article deals with the optimization of the shape of an ESP used in a small heat source. After the ESP's connection to the heat source, the mass concentration of particulate matter was measured, and the ESP's efficiency and suitability for practical use were evaluated.

2. Materials and Methods

2.1. Design of the Used Electrostatic Precipitator

The electrostatic precipitator (ESP) was placed between the inlet and outlet chimney pipes. The individual components of the ESP (T-pieces, parts of the separator pipe, knee pipes) were inserted into each other and created the U-shape. The flue gases then passed from the small heat source into the chimney tract created in this way, while the flow of flue gases was directed for the initial separation of larger particulate matter from the flue gas flow. In the two parts of the separator pipe, there were threaded rods fixed with electrically non-conductive pads and connected to an external voltage source. These rods had the function of electrodes. The connection of threaded rods to an external voltage source caused medium-sized and smaller particulate matter to be separated by the electrostatic separation force. By passing around the negatively charged threaded rods, the PM particles were also negatively charged and were subsequently attracted to the positively charged surface of the chimney pipes. Electrically non-conductive pads performed the insulating function. The electrostatic precipitator connected to the used heat source is shown in Figure 1.

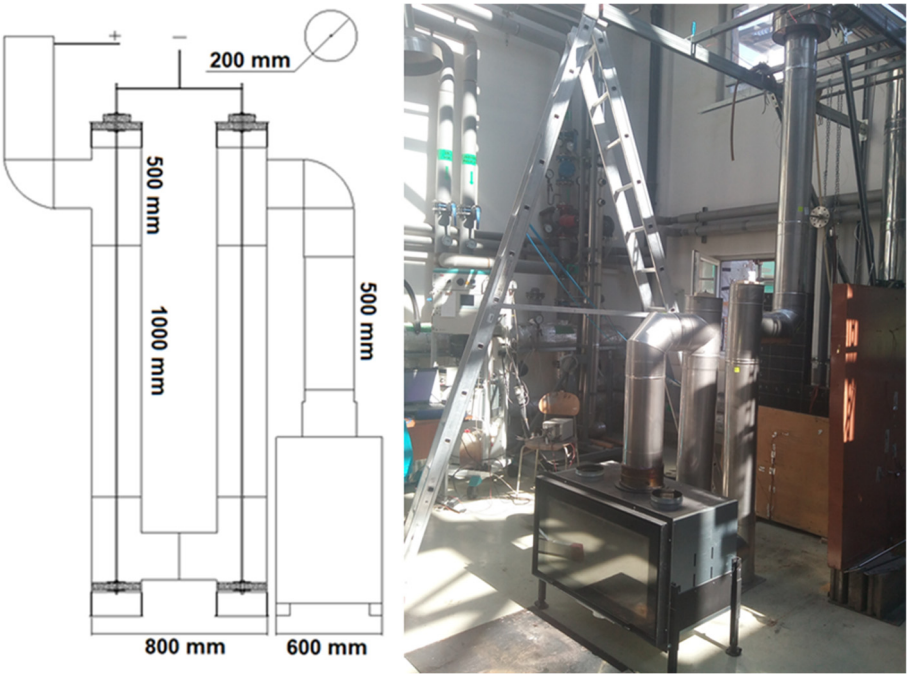


Figure 1. The combustion device with the optimized electrostatic precipitator.

2.2. Combustion Conditions

The created ESP device was connected to the fireplace Venus 850 with a nominal power of 7.4 kW and a theoretical combustion efficiency of 80.5%. Beech wood with a lower calorific value of 16.8 MJ.kg^{-1} and a weight approximately of 2.7 kg was used as fuel. For each measurement, two pieces of beech wood of approximately the same size without bark were used, placed in the same way from the back and front sides of the combustion device at the same initial chimney temperature of 180 ± 2 °C and constant chimney draft of 12 ± 2 Pa. During all experiments, the same supply of combustion air was set in the

laboratory, and the same air temperature of 24.2 ± 2 °C, the same relative humidity of 49 ± 1% and the same atmospheric air pressure of 982 ± 2 hPa were also set.

The high-voltage power supply CX-600A with a power of 300 W and a voltage of 60 kV was used for the creation of the electrostatic force. Estimated production costs should not exceed EUR 400 for 1 piece of the designed electrostatic precipitator. In the case of industrial production, the price of the device could drop by at least one-third.

2.3. Sampling of Particulate Matter

Particulate matter was sampled by a three-filter gravimetric probe placed in the flue pipe of the chimney according to a gravimetric method based on the standard STN ISO 9096 [16]. The used probe shown in Figure 2 allowed the measurement of the concentration of particulate matter in three following particle sizes: PM > 10, PM 10–2.5 and PM < 2.5.

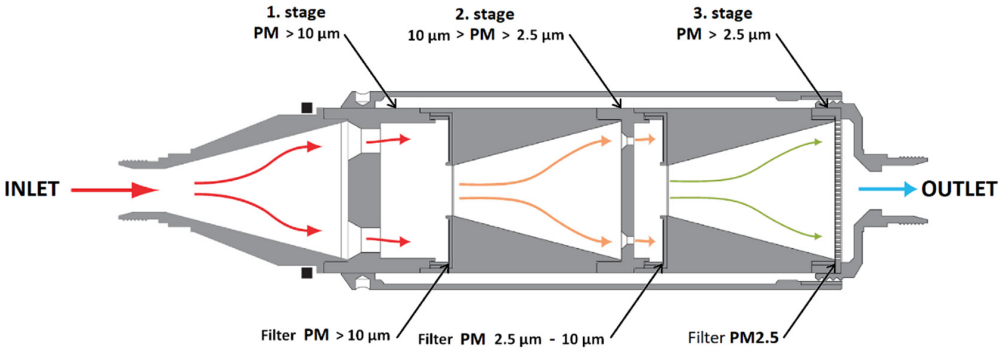


Figure 2. The principle of the used gravimetric probe.

The evaluation device Tecora Isostack Basic was connected to the gravimetric probe together with the following components: a Pitot tube, a cooling box and a silica gel dryer. Further, the samples were taken by a probe from flowing gas and particles were caught on filters. Filters were weighed before and after measurements, and the final mass concentration was calculated according to Equation (1).

$$C = \frac{m_2 - m_1}{V_{gn}} \quad (1)$$

In Equation (1), C (mg·m^{-3}) means the concentration of particulate matter in dry gas, m_1 (mg) is the filter weight before measurement, m_2 (mg) is the filter weight after measurement and V_{gn} (m^3) is the sample volume. The conversion to the concentration of particulate matter under reference conditions C^r (mg·m^{-3}) was realized according to Equation (2), where O_{2ref} (%) means the reference content of oxygen and O_{2oper} (%) means the oxygen content for operating conditions during measurement.

$$C^r = \frac{20.95 - O_{2\,ref}}{20.95 - O_{2\,oper}} \cdot C \quad (2)$$

The accuracy of this method was influenced by several parameters, mainly differential pressure in Pitot tube ± 4 Pa, temperature of flue gas ± 0.7% K, flow rate and volume measure ± 2% and filter weight ± 0.1 mg. The sampling was isokinetic, and the isokinetic deviation during all experiments was in the range −4.5 ÷ 3.8%. The isokinetic condition was achieved by a suitable shape of the sampling probe and also by a suitable velocity according to Equation (3).

$$w_{s,j} = w_i \;\rightarrow\; c_{s,j} = c_i \quad (3)$$

In Equation (3), it is important that the velocity in the probe inlet $w_{s,j}$ and the velocity of flow gas w_i are equal. Afterward, the concentration in the probe inlet $c_{s,j}$ is the

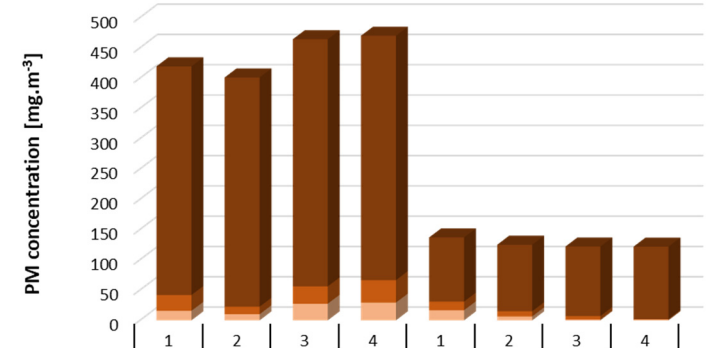
same as the concentration of flow gas c_i. The aspirated flow was regulated to achieve isokinetic conditions.

Aside from the gravimetric method, there are different measurements for the concentration of particulate matter. The radiometric method is based on measuring the weight of separated particles by absorption of the beta device in the particle layer. The concentration of particulate matter can be detected by an aerodynamic particle counter by accelerating the flow of the aerosol sample through the throat or using the spectrometer for scanning particle mobility. However, the gravimetric method is the most reliable method. Therefore, the concentration of particulate matter has been measured using the gravimetric method in this study.

Eight measurements were realized; four measurements were taken with the implementation of the electrostatic precipitator and compared with the other four measurements without the ESP device. The measurements of particulate matter were repeated three times. The mentioned result values stated in the next section are average values from these repetitions. The average standard deviation was also detected based on evaluation in the Excel program.

3. Results

Figure 3 shows the results from the measurements of the concentration of particulate matter under reference conditions. The average mass concentration of all four measurements without the use of the electrostatic precipitator was approximately 438.60 mg·m^{-3}. The average mass concentration of all four measurements with the implementation of the electrostatic precipitator was approximately 126.33 mg·m^{-3}. Based on these data, it can be summarized that the created ESP could catch approximately 71% of solid particles. However, particles are deposited on the electrodes during the operation of the used separator. This means that the real ability to capture particulate matter could be lower than 71%. Due to possible clogging, irregular cleaning and maintenance under normal conditions, an average separation efficiency (SE) of 50–60% can be expected.



	without ESP				with ESP			
F3 (PM<2.5)	377.58	378.58	408.09	403.62	105.99	109.84	114.99	119.84
F2 (PM10-2.5)	26.13	12.39	28.70	37.01	14.20	8.55	5.82	0.86
F1 (PM<10)	15.62	10.07	27.36	29.24	16.68	6.48	1.08	0.97

Figure 3. The concentrations of particulate matter.

The calculated average value of standard deviation was ± 37 mg·m^{-3} for gravimetric measurements without ESP and ± 10 mg·m^{-3} for gravimetric measurements with ESP. Individual deviations in measurement were caused by automatic regulation of the flow necessary for isokinetic conditions or changes in pressure rations on the chimney and in the laboratory space.

The individual collecting filters are presented in Figure 4. The higher difference in clogging of the filters with particles with (a–d) and without (e–h) the use of the ESP can be observed mainly for filters F1 and F2, which corresponds to particles larger than 2.5.µm.

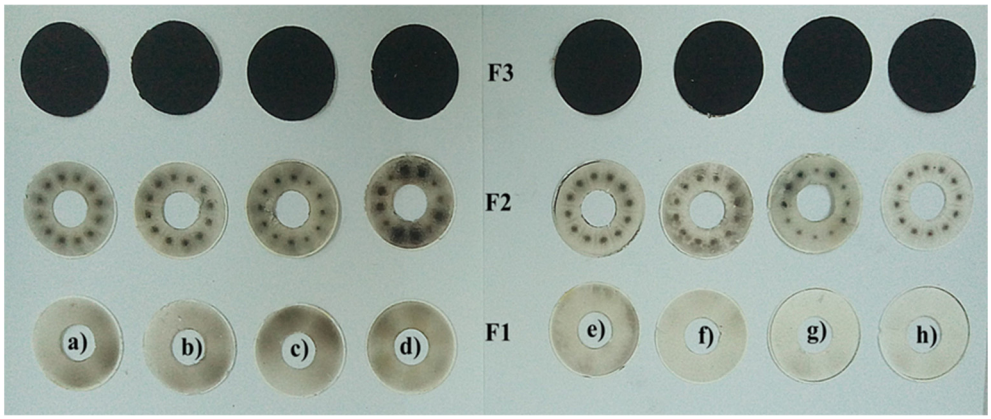


Figure 4. The individual collecting filters: (**a**–**d**) filters for measurements 1–4 without the use of the ESP; (**e**–**h**) filters for measurements 1–4 with the use of the ESP.

Mass use of this type of electrostatic precipitator could lead to a significant reduction in PM concentration in the air. When considering a model village with parameters similar to a village in the district of the city of Žilina in the north of the Slovak Republic, we can consider the following input data:

- Number of inhabitants of the model village: 5000.
- Average number of inhabitants of one household: 3.
- Considered number of households of the model village: 1667.
- Considered distribution of the energy source for household heating and hot water heating: biomass 45%, natural gas 40%, coal 10%, others (electric energy—electric boilers, heat pumps).
- Average annual heat demand: 20,000 kWh.

From the input data, 55% of households generate particulate matter during the operation of heat sources. In the model village, these heat sources are divided into the following categories:

- Biomass heat source worse than the third emission class of STN EN 303-5 (13.5% of all households) with estimated PM production at the level 1.2 g/kWh (B1-2).
- Biomass heat source third emission class of STN EN 303-5 (11.25% of all households) with estimated PM production at the level 0.6 g/kWh (B3).
- Biomass heat source fourth emission class of STN EN 303-5 (11.25% of all households) with estimated PM production at the level 0.3 g/kWh (B4).
- Biomass heat source fifth emission class of STN EN 303-5 (9% of all households) with estimated PM production at the level 0.15 g/kWh (B5).
- Coal heat source worse than the third emission class of STN EN 303-5 (3% of all households) with estimated PM production at the level 1.8 g/kWh (C1-2).
- Coal heat source third emission class of STN EN 303-5 (2.5% of all households) with estimated PM production at the level 0.9 g/kWh (C3).
- Coal heat source fourth emission class of STN EN 303-5 (2.5% of all households) with estimated PM production at the level 0.4 g/kWh (C4).
- Coal heat source fifth emission class of STN EN 303-5 (2% of all households) with estimated PM production at the level 0.2 g/kWh (C5).

The considered model village with no use of electrostatic precipitators (ESPs) could generate approximately 12.24 tons of PM per year (Table 1) [4]. If the application of ESPs to all heat sources of the oldest construction of the first and second emission classes of STN EN 303-5 (B1-2 and C1-2; 1–2 class) would be considered, PM production would be reduced by almost 29.5% to 8.64 t/year considering 50% separation efficiency (SE) and more than 35% to 7.92 t/year considering 60% separation efficiency. If ESPs were also applied to all heat sources of the third emission class (B1-2, B3, C1-2 and C3; 1–3 class), PM production

would be reduced by almost 42% to 7.14 t/year considering 50% SE and 50% to 6.12 t/year considering 60% SE. If ESPs were also applied to all heat sources of the fourth emission class (B1-2, B3, B4, C1-2, C3 and C4; 1–4 class), PM production would be reduced by almost 48% to 6.41 t/year considering 50% SE and more than 57% to 5.25 t/year considering 60% SE. If ESPs were applied to all heat sources for burning solid fuels for all emission classes (B1-2, B3, B4, B5, C1-2, C3, C4 and C5; 1–5 class), PM production would be reduced by 50% to 6.12 t/year considering 50% SE and 60% to 5.25 t/year considering 60% SE.

Table 1. Total PM production in the model village without the use of ESPs and with different scenarios of the ESP use.

PM Emissions	Without ESP	ESP for 1–2 Class, SE 50%	ESP for 1–2 Class, SE 60%	ESP for 1–3 Class, SE 50%	ESP for 1–3 Class, SE 60%	ESP for 1–4 Class, SE 50%	ESP for 1–4 Class, SE 60%	ESP for 1–5 Class, SE 50%	ESP for 1–5 Class, SE 60%
	t/Year								
B1-2	5.40	2.70	2.16	2.70	2.16	2.70	2.16	2.70	2.16
B3	2.25	2.25	2.25	1.13	0.90	1.13	0.90	1.13	0.90
B4	1.13	1.13	1.13	1.13	1.13	0.56	0.45	0.56	0.45
B5	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.23	0.18
C1-2	1.80	0.90	0.72	0.90	0.72	0.90	0.72	0.90	0.72
C3	0.75	0.75	0.75	0.38	0.30	0.38	0.30	0.38	0.30
C4	0.33	0.33	0.33	0.33	0.33	0.17	0.13	0.17	0.13
C5	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.07	0.05
TOTAL	**12.24**	**8.64**	**7.92**	**7.14**	**6.12**	**6.41**	**5.25**	**6.12**	**4.90**

In real conditions, however, it is not possible to assume that it would be possible to apply ESPs to all required heat sources of the relevant emission classes even with the use of changes in legislation or subsidies. Table 2 shows the change in PM production when applying ESPs to households with 50%, 60%, 70%, 80% and 90% proportions.

Table 2. Total PM production in the model village in more realistic conditions.

PM Emissions	ESP for 1–2 Class, SE 50%	ESP for 1–2 Class, SE 60%	ESP for 1–3 Class, SE 50%	ESP for 1–3 Class, SE 60%	ESP for 1–4 Class, SE 50%	ESP for 1–4 Class, SE 60%	ESP for 1–5 Class, SE 50%	ESP for 1–5 Class, SE 60%
	t/Year							
0% applied ESPs	12.24							
50% applied ESPs	10.44	10.08	9.69	9.18	9.33	8.75	9.18	8.57
60% applied ESPs	10.08	9.65	9.18	8.57	8.75	8.05	8.57	7.84
70% applied ESPs	9.72	9.22	8.67	7.96	8.16	7.35	7.96	7.10
80% applied ESPs	9.36	8.79	8.16	7.35	7.58	6.65	7.35	6.37
90% applied ESPs	9.00	8.36	7.65	6.74	7.00	5.95	6.73	5.63
100% applied ESPs	8.64	7.92	7.14	6.12	6.41	5.25	6.12	4.90

It is possible to assume that the implementation of the separator would be implemented gradually for individual households. Moreover, not all households would be willing to participate, which would reduce the overall separation ability in the model village and also increase the considered amount of emissions in the air.

In the model village, the average annual concentration of solid particles PM10 is at the level of 25 $\mu g/m^3$ and PM2.5 is at the level of 19 $\mu g/m^3$ [4]. The share of heat sources is 62.1% for PM10 and 79% for PM2.5 in the air [3]. Based on the assumption that small heat sources have the greatest influence on the concentration of PM in the air, Table 3 lists the predicted average concentrations of PM10 and Table 4 lists the predicted average concentrations of PM2.5 after the application of ESPs to the relevant scenarios listed in the previous tables.

Table 3. Average annual PM10 concentrations in the air of the model village.

PM10 Emissions	ESP for 1–2 Class, SE 50%	ESP for 1–2 Class, SE 60%	ESP for 1–3 Class, SE 50%	ESP for 1–3 Class, SE 60%	ESP for 1–4 Class, SE 50%	ESP for 1–4 Class, SE 60%	ESP for 1–5 Class, SE 50%	ESP for 1–5 Class, SE 60%
				μg/m^3				
0% applied ESPs				25				
50% applied ESPs	22.72	22.26	21.77	21.12	21.30	20.56	21.12	20.34
60% applied ESPs	22.26	21.71	21.12	20.34	20.56	19.68	20.34	19.41
70% applied ESPs	21.80	21.16	20.47	19.57	19.83	18.79	19.57	18.48
80% applied ESPs	21.35	20.62	19.83	18.79	19.09	17.90	18.79	17.55
90% applied ESPs	20.89	20.07	19.18	18.01	18.35	17.02	18.01	16.62
100% applied ESPs	20.43	19.52	18.53	17.24	17.61	16.13	17.24	15.69

Table 4. Average annual PM2.5 concentrations in the air of the model village.

PM2.5 Emissions	ESP for 1–2 Class, SE 50%	ESP for 1–2 Class, SE 60%	ESP for 1–3 Class, SE 50%	ESP for 1–3 Class, SE 60%	ESP for 1–4 Class, SE 50%	ESP for 1–4 Class, SE 60%	ESP for 1–5 Class, SE 50%	ESP for 1–5 Class, SE 60%
				μg/m^3				
0% applied ESPs				19				
50% applied ESPs	16.79	16.35	15.87	15.25	15.43	14.71	15.25	14.50
60% applied ESPs	16.35	15.82	15.25	14.50	14.71	13.85	14.50	13.60
70% applied ESPs	15.91	15.29	14.62	13.75	14.00	13.00	13.75	12.70
80% applied ESPs	15.47	14.76	14.00	13.00	13.28	12.14	13.00	11.80
90% applied ESPs	15.03	14.23	13.37	12.25	12.57	11.28	12.25	10.89
100% applied ESPs	14.59	13.70	12.75	11.50	11.85	10.42	11.50	9.99

Considering production costs of EUR 300 per piece of equipment and installation costs of EUR 200 per household and considering that the equipment will be implemented for each heat source of the first and second emission classes, the costs could represent approximately EUR 412.500. If electrostatic precipitators were implemented in every household with a solid fuel heat source, the expected costs would be EUR 1.375 million. Part of these costs could be borne by the municipality, and funding could also be obtained through various environmental calls for projects.

4. Conclusions

Looking at possibilities for how to decrease emissions and solid aerosols in the atmosphere in an affordable and effective way is an important issue. This article focuses on a low-cost electrostatic precipitator and its implementation in small heat sources. The designed ESP type could catch approximately 71% of solid particles based on the gravimetric measurement of mass concentration of particulate matter. However, the real ability to capture particulate matter could be lower due to deposited particles on the electrodes during the operation of the used separator. Therefore, an average separation efficiency of 50–60% could be expected.

Further, the article deals with the application of the village model with this type of electrostatic precipitator in households. The village could generate approximately 12.24 tons of PM per year without ESP use according to this model. With the consideration of the application of ESPs to all heat sources of the oldest construction of the first and second emission classes of STN EN 303-5, PM production would be reduced by almost 29.5% to 8.64 t/year considering 50% separation efficiency and more than 35% to 7.92 t/year considering 60% separation efficiency; upon further application of ESPs to all heat sources of the third emission class, PM production would be reduced by almost 42% to 7.14 t/year considering 50% separation efficiency and 50% to 6.12 t/year considering 60% separation efficiency; upon further application of ESPs to the sources of the fourth emission class, PM production would be reduced by almost 48% to 6.41 t/year considering 50% separation efficiency and more than 57% to 5.25 t/year considering 60% separation efficiency; and

finally, upon application of ESPs to all emission class, PM production would be reduced by 50% to 6.12 t/year considering 50% separation efficiency and 60% to 5.25 t/year considering 60% separation efficiency. However, this has been described as the ideal situation, but it is not possible to assume that it would be possible to apply ESPs to all required heat sources of the relevant emission classes even with the use of changes in legislation or subsidies in real conditions.

In general, households have the most significant proportion of air pollution by particulate matter. The application of the village model presented in this article leads to a decrease in emissions of particulate matter in households and thus better quality of the environment and also life. The improvement of life quality can cause a reduction in respiratory and cardiovascular diseases arising because of air pollution. However, several factors have a significant impact on this model, such as dispersion conditions or emissions penetrating from surrounding areas. Therefore, the presented model should have a more important impact when applied across the whole country, for example, within the whole republic.

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