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Numerical model expressing the amount of capture of particulate matter by an electrostatic precipitator for small heat sources

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Abstract: The article deals with the issue of air pollution by particulate matter. At present, there is a high production of these substances in the sector of heating with small heat sources, compared to the automotive or energy industry. The purpose of this article was to create an experimental numerical model of an electrostatic precipitator and to calculate its efficiency of particle capture in a simulated community.

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1 Introduction

The protection of human health is a very serious issue, especially today. Therefore, from our point of view, it is important to explore comprehensive options for reducing air pollution by human activity. EU action is also leaning towards protecting the environment, which is increasingly tightening emission limits [1]. The impact of such measures can be observed in the automotive industry, where more and more efforts are beginning to focus on the development and production of electric cars, hybrid vehicles, respectively. exploring alternative fuels [2]. In this area, the production of particulate matter (PM) is succeeding, but the area of heating with small heat sources lags far behind [3-5]. PM can have a serious negative impact on human health, especially on the respiratory tract. Figure 1 is a warning finger in the form of a graph showing the number of years of life lost per 100 inhabitants due to air pollution. Given the local conditions, it can be argued that Slovakia has climbed too high. From this point of view, it is logical to address the issue of reducing emissions even in non-industrial sectors, where the legislation is not as strict as in industrial sectors.

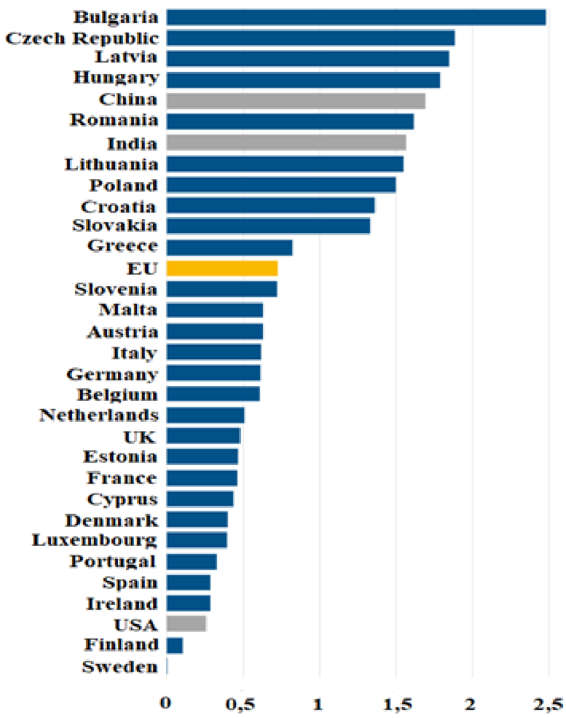

Figure 1 The number of years of life lost per hundred inhabitants due to air pollution [3]

2 Particulate matter

PM are particles of a pollutant of any shape, structure or density dispersed in the gas phase. According to size, they are divided into two basic groups:

- coarse particles PM10 (solid particles ≤ 10 micrometres = μm) - for better clarity only the size of 10 micrometres is smaller than the width of one human hair, with this size the particles can easily penetrate the lung tissues, where they settle, which over time can in the human body provoke a variety of health problems in the cardiovascular and respiratory systems. Sources of coarse particles are, for example: whirling dust from industrial roads, combustion of solids or exhaust gases from motor vehicles.
- fine particles PM 2.5 (solid particles ≤ 2.5 micrometres = μm) - these particles are so small that they can only be detected by electron microscopy. Sources of fine particles include all types of combustion processes, including residential wood burning, forest fires, power plants, agricultural processes, road transport, etc.

PM have multiple negative effects on human health (Table 1), with perhaps our airways suffering the most, which is because the only route of exposure for PM to the human body is inhalation.

Table 1 Effects of emissions on human health [3]

WHAT ARE THE EFFECTS ON HUMAN HEALTH	
$PM_{2,5}$	Stroke
O_3 ; PM ; NO_2 ; SO_2	Respiratory disease
PM	Lung diseases and lung cancer
O_3 ; PM ; SO_2	Cardiovascular disease
NO_2	Liver and blood disease

2.1 PM capture

There are several methods for capturing these particles, the most effective of which is electrostatic precipitation technology. This technology is very widespread in industrial production, where electrostatic precipitators reach a size of more than 6 m, but they are slowly being used in small heat sources, in the heating of family homes. It is in this sector that great efforts are needed to capture PM, because even compared to transport, the heating sector lags far behind in the statistics. There is also progress in this area on the development of alternative fuels that would reduce emissions and could be an adequate replacement for fossil fuels Holubčík [6] and Jandačka [7] and Variny [8]. Nowadays, automatic boilers for burning wood pellets are used more and more, which brings with them more advantages Holubčík [9]. The transition to this type of fuel significantly affects the environmental load, as pellets are produced from wood waste and thus relieve the production process from the production of emissions compared to fossil fuels to a large extent.

2.2 Electrostatic precipitation

Electrostatic precipitators are devices that, with proper optimization, can achieve efficiencies of up to 95%. They work on the principle of electrostatic precipitation of electrically conductive particles. They consist of two main electrodes, discharge and collecting. The discharge electrode is a conductive wire, fixed and insulated by insulators in the chimney. This electrode is connected to a negative source of high DC voltage 30-50kV. The positive pole of the voltage source is connected to the collecting electrode. This is represented by a conductive plate placed on the inner surface of the chimney. Figure 2 shows how particles react in electrostatic field.

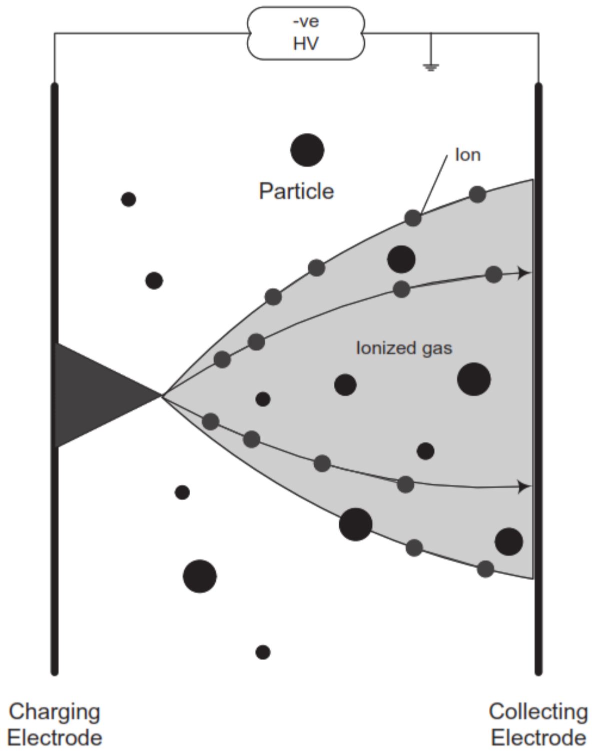

Figure 2 Behaviour of the particles in electrostatic field [10]

PM, which proceed from the boiler to the chimney, are charged with a negative charge by the discharge electrode and attracted by the opposite charge of the collecting electrode. This captures PM at the collecting electrode. In order for the process to be complete and efficient, it is necessary to arrange for cleaning of the collecting electrode from trapped particles, as clogging of the collecting electrode has a negative effect on the capture of PM in the precipitator. Among the precipitators that are already used today, resp. are part of the research, we distinguish precipitators located vertically on the upper part of the chimney, in the lower part of the chimney (Figure 3) or located horizontally between the boiler and the chimney.

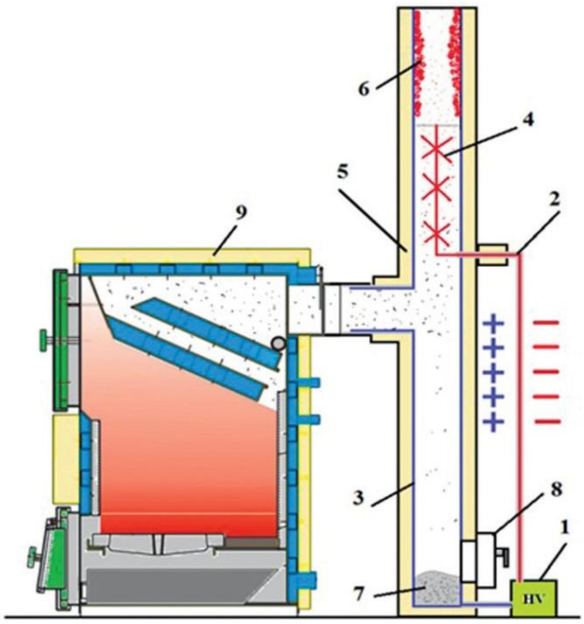

Figure 3 1 - high voltage source, 2 – charging electrode, 3 – collecting electrode, 4 – voltage concentration, 5 – insulation, 6 – settled dust, 7 – captured PM, 8 – open [11]

3 Numerical model

The following section will describe an experiment in which the effects of the use of electrostatic precipitators in the model community were assessed. PM productions from heating in small heat sources without and with PM capture were compared. The considered model municipality included 500 households with different heat sources. The calculations assumed that the heating period in the area is 240 days and the average daily heating time is 7 hours. The numbers of individual heat sources were chosen randomly. Table 2 shows the types and numbers of heat sources in households, in Table 3 you can see the types of fuels used.

Table 2 Types and numbers of heat sources

MODEL VILLAGE	Number of heat sources
Condensing boiler	150
Combination boiler	100
Fireplace	70
Gasification boiler	80
Automatic boiler	100

Table 3 Types of Fuel

Fuel
Dry wood (8% humidity)
Wood (20% humidity)
Wood (40% humidity)
Brown coal
Black coal
Wood briquettes
Waste

Table 4 shows the selected parameters of the electrostatic precipitator, which were considered in the particle capture calculations. The selected separator is a device inserted at the bottom of the chimney space behind the boiler.

Table 4 Parameters of Electrostatic precipitator

ELECTROSTATIC PRECIPITATOR			
LIST	SYMBOL	VALUE	UNIT
Gas flow	Q	0,05	$m^3 \cdot s^{-1}$
Active precipitator length	L	2	m
Rate of precipitation	w	0,07	$m.s^{-1}$
Radius of collecting electrode	R	0,075	m
Gas flow rate	v	2,829	$m.s^{-1}$
Residence time	τ_S	0,707	s
Precipitation time	τ_O	1,1	s
Projection of the collecting electrode area	S	0,471	m^2
Specific settling area	f	9,4	$s.m^{-1}$
Waste	P	0,267	-
Separability	O	**0,73**	-

Different fuel variants were used for each type of heat source. Table 5 shows the PM productions for combustion boilers. Because the scope of this article is limited, Table 5 and Table 6 serve to clarify the achieved results of PM production. For every types of boilers, the production of PM was calculated in the same way, but for the purposes of the article, all these data will be summarized in table.

Table 5 PM production for combustion boilers

Fuel	Heat value	Flue gas production	Efficiency	Fuel consumption	Amount of flue gas	PM production	PM production
	[MJ.kg^{-1}]	[m^3.kg^{-1}]	[%]	[kg.h^{-1}]	[m^{3}h^{-1}]	[mg.m^{-3}]	[g.h^{-1}]
Dry wood (8% humidity)	16,5	10	70	6,23	62,34	100	6,23
Wood (20% humidity)	14,1	10	70	7,29	72,95	200	14,59
Wood (40% humidity)	10,1	10	70	10,18	101,84	400	40,74
Brown coal	20,6	10	70	4,99	49,93	350	17,48
Black coal	29,7	10	70	3,46	34,63	250	8,66
Wood briquettes	19	10	70	5,41	54,14	150	8,12
Waste	11	10	70	9,35	93,51	2000	187,01

Table 6 PM production for condensing boiler

Fuel	Number of heat sources		PM production	
Dry wood (8% humidity)	15		93,51	
Wood (20% humidity)	38		554,41	
Wood (40% humidity)	22		896,18	
Brown coal	30		524,27	
Black coal	23		199	
Wood briquettes	7		56,84	
Waste	15		2805,19	
Value	150	pcs	5129,5	g.h^{-1}

In Table 7, the annual PM productions of all considered boilers in the simulated area are expressed, together with the total calculated amount captured by PM by electrostatic precipitators. Their value reached almost 8.5 tons per year, which represents approximately ¾ captured PM from total production.

Table 7 Captured amount of PM per year.

MODEL VILLAGE	Number of heat sources	Flue gas production per year	Captured amount of PM
Condensing boiler	150	8617,62	6116,33
Combination boiler	100	1570,44	1114,62
Fireplace	70	952,93	676,34
Gasification boiler	80	468,8	332,73
Automatic boiler	100	348,12	247,08
Value	500	11957,9	8487,09
	pcs	kg.year^{-1}	kg.year^{-1}

4 Conclusions

The article dealt with the topic of PM capture in small heat sources using electrostatic precipitators. A numerical model was performed including the calculation of the amount of PM captured in one year in a simulated area with 500 heat sources. The total flue gas production per year reached almost 12 tons per year. The proposed precipitator would be able to capture 73 % of PM, which is almost 8.5 tons per year. This number could be increased significantly higher by appropriate optimization. On the contrary, the overall reduction of PM produced could be achieved by using quality fuels such as dry wood, black coal, briquettes...

As the state of the environment is under scrutiny worldwide and alarming in some areas, it is necessary to look for solutions to protect and maintain your environment. If we want to move forward as humanity, we must use our skills and technical capabilities not to destroy our planet, but to protect it.

Acknowledgement

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