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BEHAVIOUR OF ELECTROSTATIC FILTERS IN TERMS OF CO-COMBUSTION OF BROWN COAL AND BIOMASS

PONAŠANJE ELEKTROSTATIČKIH FILTERA KOD KOSAGORIJEVANJA MRKOG UGLJA I BIOMASE

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Abstract: While there isan increasing number of publications on the problems encountered in co-combustion of coal and biomass in traditional boilers, there are still not many papers with the experimental results regarding electrostatic filters in these conditions. In the thermal power plant "Kakanj", an experimental study was implemented on the effects of co-combustion of brown coal and biomass (wood chips), primarily with the aim of monitoring the effects on CO_2 emissions and the state of the boiler. Experimental co-combustion of coal and biomass has been used to explore the behaviour of the electrostatic filter. Monitoring the behaviour of electric values of the electrostatic filter was carried out in a campaign of brown coal combustion only, and in the campaign of co-combustingbrown coal and biomass.

Keywords: electrostatic precipitator, co-combustion, biomass, separation efficiency

Sažetak: Iako postoji sve veći broj publikacija o problemima koji se susreću u kosagorijevanju uglja i biomase u tradicionalnim kotlovima, još uvijek postoji mali broj radova s eksperimentalnim rezultatima u pogledu rada elektrostatskog filtera u tim uvjetima. U termoelektrani "Kakanj" realizirano je eksperimentalno istraživanje efekata kosagorijevanja mrkog uglja i biomase (drvna piljevina), prvenstveno s ciljem promatranja efekata na emisiju CO_2 i stanja u kotlu. Eksperiment kosagorijevanja uglja i biomase iskorištenje i za istraživanje ponašanjaelektrostatskog filtera. Posmatranja ponašanja električnih veličina elektrostatskog filtera vršenasu u kampanji sagorijevanja samo mrkog uglja, a potom u kampanji kosagorijevanja mrkog uglja i biomase.

Ključne riječi: elektrostatski filter, kosagorijevanje, biomasa, efikasnost izdvajanja

INTRODUCTION

The coal-fired thermal power plants discharge a large amount of flue gases with the contents of the floating particles of coal dustinto the environment. Today, various devices are used to extract particles from the stream of flue gas generated by coal firing, and electrostatic filters are one of the most commonly used. Electrostatic filters can clean large volumes of flue gas at a certain range of temperature, pressure and dust concentration.

For many industrial applications the efficiency of electrostatic filters used to extract floating particles from flue gas streams reaches 99%. The electrostatic filter is not always a suitable particle separator because it works on the principle of electrostatic attraction, which means that its efficiency is conditioned by the ability to create electric charge on floating particles in the electrodes interface. In unfavourable conditions for creationof electric charge on ash particles, measures for the conditioning of flue gases are used to create more favourable conditions.

The main motive for the use of biomass as a second fuel in thermal power plants is the reduction of CO2 emissions, but also the financial benefits offered in accordance with the relevant international regulations.

The basic aim of the experiment was to confirm the possibility of introducing the technology of wood biomass and coal combustion technology to thermal power plant (TPP) "Kakanj". The biomass co-combustion experiment on boiler 5 in TPP "Kakanj" was also used to investigate the behaviour of the electrostatic filter.

An observation of the behaviour of the characteristic size of the electrostatic filter was carried out in the campaign of combustion of only brown coal and then in the campaign of 7% biomass (wood sawdust) in the mixture. Wood sawdust was supplied from saw mills and wood processing plants in the environment.

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1. CREATING PARTICLE CHARGING

A typical electrostatic filter is shown in Figure 1.

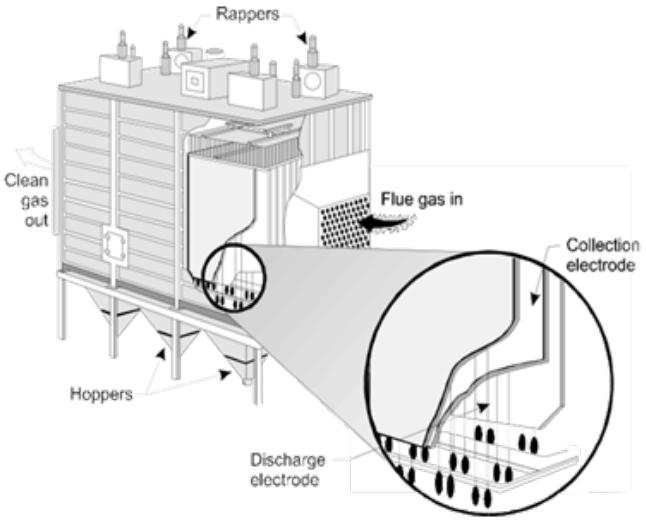


Figure 1: Electrostatic filter [1]

Emission electrodes are usually thin wires, evenly spaced between large grounded metal plates - collecting electrodes. Emission electrodes are under negative pulsating high voltage, which creates a very electric field in the surrounding space. The electrical field is the strongest to the emission electrodes, weaker in the area between the emission and collecting electrodes, and the weakest near the collecting electrode. The process of creating electric charge to the floating particles in the flue gas stream begins in the area around the emission electrodes (Figure 2). After the establishment of a strong electric field several processes start in the interstate of the electrodes:

a. Corona discharge -creating free electrons

The voltage from the high voltage rectifier increases until the corona appears, which is recognized as a bright blue light around the emission electrodes. Free electrons, created by coronary action, accelerate rapidly and quickly migrate from a negative electric field. This acceleration causes their crashes with gas molecules and the release of other electrons from molecules. As a result of the loss of electrons, the gas molecules become electrically positively charged so that they turn in positive ions, Figure 2. All these activities occur near the emission electrodes. This process continues by creating more and more free electrons and positive ions [1].

On the other hand, positive ions under the action of a strong electric field are attracted to a negative emission electrode. Molecules are significantly larger than electrons and are moving slower. In fact, many of them crashed with electrons emitted by electrodes or arrive from space around.

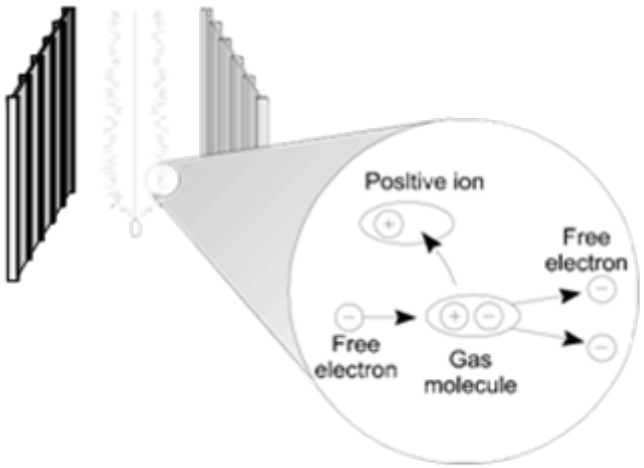


Figure 2: Ionisation of gas molecules created due of corona [1]

b. Ionisation of gas molecules

Migrating from the space of a strong negative electric field around the emission electrodes, the electrons begin to slow down. In the interstate they are still under the action of the emission electrodes, but to a lesser extent. There are also gaseous molecules present; electrons collide to the molecules that accept them, Figure 3. It gives a negative electric charge to the gas molecules producing negative gas ions. The ionisationof the gas molecule occurs near of the emission electrodes, but different from ionisation in the interstate. Ions near the electrodes emission are positive and are retained in the area.The ions in the middle region are negative and move to the collecting electrode.

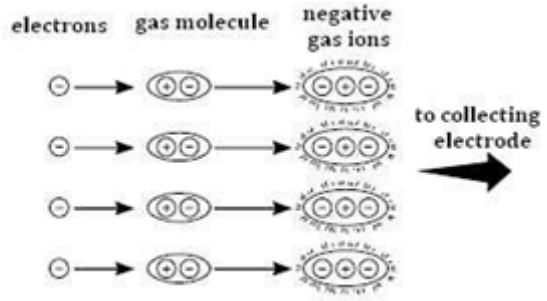


Figure 3: Creating negative gas ions in the interelectrode space [1]

c. Charging of particles

Negative ions of gas play a key role in extracting dust particles from flue gases. In order to separate the dust particles, they must first get a negative electric charge. Migrant through the smoke stream of dust, particles meet and accept negative gas jets and thus receive a negative charge. Initially, the charge is rather insignificant because most dust particles are huge compared to gas molecules. However, the particle can accept many ions of gas, and will form a significant negative electric charge. Small particles with a

diameter smaller than 1 μm can absorb dozens of ions. Large particles with diameters greater than 10 μm can absorb tens of thousands of ions. Finally, so many ions attach to the particle that it creates a negative electric field around it, and prevents further acceptance of new ions. In this way, the particles become charged with saturation Large particles have a higher charge of saturation, and their attraction to the collecting electrode is stronger. Regardless of the particle size, they will be collected on the collection electrode. On the collection electrode thicker layer of dust is formed by depositing a large number of particles.

Creation of electrical charge on dust particles is done in two ways: by the action of an electric field and the diffuse movement of particles in the space between the electrodes. In a strong electric field, dust particles accept the negatively charged ionic gas that moves to the collecting electrode. In a strong electric field, dust particles absorb negatively charged ions that move to the collecting electrode. Electrically charged dust particles enter the electric field and locally deform it, Figure 4.

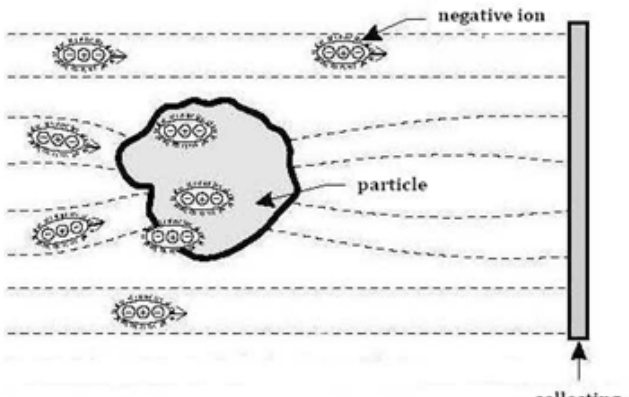
Charge spherical particles of dust (q_f) generated by the action of an electric field, is time dependent and is given by the following equation [2]:

$$q_f(t) = q_s \cdot \frac{t}{t+\tau} \tag{1}$$

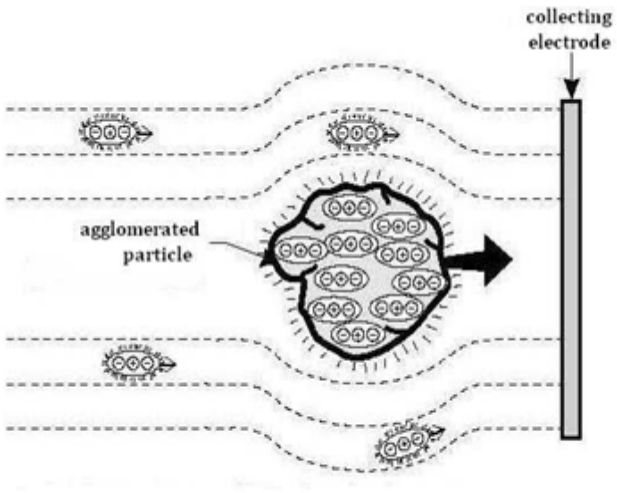
Where:

q_s - saturation charge of the particle (C),
t - time of creating the electric charge (s),
τ - time constant of creating electric charge (s).

Negative gas ions, migrating through the space between the electrodes, bump into particles and transmit their charge to them. Ions will continue colliding with particles until the charge of theparticle becomestoo small to redirect them, respectively, until the particles reach the saturation charge. Particles, saturated with electric charge, migrate to the collecting electrode, and are deposited there.



a) Deformation of the electric field due to particles



b) Agglomerated particles on the path to the collecting electrode

Figure 4: Creating electric charge particles due acting from electric field [1]

The charge saturation spherical particles is given by [2],[3]:

$$q_s = 3\pi d_p^2 \cdot E \frac{\varepsilon_0 \varepsilon_s}{\varepsilon_s + 2} \tag{2}$$

Where:

ε_0 - dielectric permissibility of vacuum,
ε_S - specific permissibility,
d_p - particle diameter (m),
E - electric field strength (V/m).

The charge saturation is proportional to the square of the diameter of a particle, which explains why the electric charging by the electric field dominant in large particles. The time constant of charging by the electric field is given as:

$$\tau = 4 \cdot \varepsilon_0 \cdot \frac{E}{J} \tag{3}$$

Where:

J - current density (A/m^2)

In diffusion charging, ions in the gas bounce around due to Brownian motion, bump into a particle, and transfer their charge to it. Negative ions of gas collide with particles due to their chaotic thermal movement and deliver their charge. Creating electric charge by diffusion is a mechanism by which very small particles become electrically charged. Thus, electrically charged particles migrate to a collecting electrode. The electric charge of particles generated by diffusion is calculated by the following equation [4]:

$$q_d(t) = q \cdot \ln\left(1 + \frac{t}{\tau}\right) \tag{4}$$

Where q is the constant of the electrical charging of the particle (C), shown by the equation:

$$q = 2\pi \cdot \varepsilon_0 \cdot d_p \cdot \frac{k \cdot T}{e}$$

d_p - diameter of particle (*m*),
k - Boltzman constant ($1.38x10^{-23}$ *J/K*),
T - absolute temperature (K),
e - charge of electron(1.67×10^{-19} *C*),
τ - time constant of diffuse charging (*s*),
given as:

$$\tau = 8\varepsilon_0 \cdot \frac{k \cdot T}{d_p \cdot C_i \cdot \eta_i \cdot e^2} = 8\varepsilon_0 \cdot \sqrt{m_i \cdot \frac{k \cdot T}{3}} \cdot \frac{\mu_i \cdot E}{d_p \cdot J \cdot e} \quad (5)$$

Where:
C_i - thermal velocity of ions (m/s),
T - temperature (K),
η_i - concentration of ions in space (1/m^3),
m_i - ion mass (kg),
μ_i - ion mobility (Vm/s^2).

The electric charge of particles generated by diffusion has a logarithmic growth, so the charge of particles at t=500$\cdot\tau$ or q_{500}= 6.2$\cdot q$, can be taken asa charge of saturation. q and q_{500} are independent of E and J, but are proportional to the temperature T[2]. The time constant diffuse charging is proportional to J^{-1}.

Although both mechanisms of generating electrical charges simultaneously operate on particles, empirically a very good approximation of particle charge can be obtained as a charge sum obtained from equations (1) and (4):

$$q_{tot} = q_d(t) + q_f(t) \quad (6)$$

Where:
q_{tot} - total charge of particles,
$q_d(t)$ - charge of the particles created by diffusion,
$q_f(t)$ - charge of particles created by an electric field.

Each of these two mechanisms of creating electrical charge on particles is going to a certain extent, and dominance of a mechanism will depend on the particle size. The creation of electrical charge by the field dominates the particles with a diameter >1.0 *μm*, because the particles have to be large enough to accept the gas ions. The creation of electric charge by diffusion dominates for particles of diameter <0.1 *μm*. The combination of these two mechanisms for creation ofelectrical charges occurs for particles whose diameter ranges from 0.2 to 1.0 *μm*.

When the electrically charged particle reaches the collecting electrode, its charge is discharged. A part of the charge particles isslowly emptied into the grounded collecting electrode. Part of the charge is retained and affects the inter-molecular adhesive and cohesive forces holding the particles on the collecting electrode, Figure 5. The adhesive forces physically hold the particles interconnected by their bumpy surfaces. The newly received electrically charged particles with cohesive forces are adhered to the deposited particle layer; the particles are attracted to each other by the molecular forces that hold them together. The dust layer is formed on the electrode to a certain thickness and then the cycle of its removal is started.

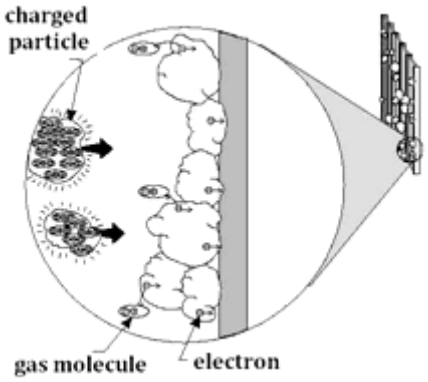


Figure 5: Particle collection at collection electrode [1]

During the process of cleaning the flow of flue gas, the collecting electrodes are periodically shaken to remove the dust layer. The electrode is shaken when the deposited layer of dust is relatively thick (0.08 to 1.27 *cm*). This allows the layer of dust to fall easily from the electrodes in the form of large leaves so that it does not return between the electrode spaces. Installations with high dust concentrations require more frequent shaking. The dust drops into the ash collector, which is in the form of a funnel and is below each set of collecting electrodes. The ashtray haveside sloping sides in order to have a free fall of the removal dust towards the delivery apparatus placed in the bottom.

d. Removal of particles

The force of the electric field acting in the inter-electrode space on the electrically charged particles is proportional to the field strength and the charge of the particles:

$$F = q + E \quad (7)$$

Where:
F - force of action from the electric field (*N*),
q - particle charge (*C*),
E - electric field (*V/m*).

Movement of the particles generated by the action of the electric field is resisted by the gas viscosity resistance. The viscous force that opposes the movement of electrically charged particles is [2]:

$$F_s = 3\pi \cdot \mu \cdot d_p \cdot \frac{w_e}{C_m} \quad (8)$$

By equating the force of action of the electric field and the force of viscosity resistance, the velocity of the particle movement to the precipitation electrode can be obtained [5]:

$$w_e = \frac{q \cdot E \cdot C_m}{3\pi \cdot \mu \cdot d_p} \tag{9}$$

$$C_m = 1 + 2.54 \cdot \frac{\lambda}{d_p} + 0.8 \cdot \frac{\lambda}{d_p} e^{-\frac{0.55}{\lambda}} \tag{10}$$

$$\lambda = 6.61 \cdot 10^{-8} \cdot \frac{T}{293} \cdot \frac{101.3 \cdot 10^3}{P} \tag{11}$$

Where:
w_e -migration velocity (*m/s*),
μ - gas viscosity (*Pa s*),
d_p - diameter of the particle (*m*),
C_m - Cunningham correction factor,
λ - the mean free path of gas molecules (*m*),
T, P- the temperature and pressure (*Pa*).

The migration velocity of the particles under the action of the electric field is [4]:

$$w_e = \frac{q \cdot E}{3\pi \cdot \mu \cdot d_p} = d_p \cdot E^2 \cdot \frac{\varepsilon_0 \cdot \varepsilon_S}{\mu \cdot (\varepsilon_S + 2)} \tag{12}$$

The migration velocity of the particles whose charge is created by the action of the electric field is proportional to the particle diameter d_p and the square of the field strength E^2.

The migration velocity of the charged particle created by diffusion is given by the equation [4]:

$$w_e = 6{,}2 \cdot E \cdot C_m \cdot \frac{2\pi \cdot \varepsilon_0 \cdot d_p \cdot \frac{K \cdot T}{e}}{3\pi \cdot \mu \cdot d_p} = 4\varepsilon_0 \cdot C_m \cdot E \cdot \frac{K \cdot T}{\mu \cdot e} \tag{13}$$

The collection efficiency is the number most commonly used in the electrostatic filter performance description and is given by Deutsch [1, 2, 5]:

$$\eta = 1 - e^{w_e f} = 1 - e^{w_e \frac{A}{Q}} \tag{14}$$

Where:
w_e - the migration velocity (*m/s*),
f=*A/q* - the specific collection area (*s/m*),
A - the area of the collecting electrode (m^2),
Q - the gas flow rate (m^3/s).

Figure 6 shows the collection efficiency depending on particle size [6].

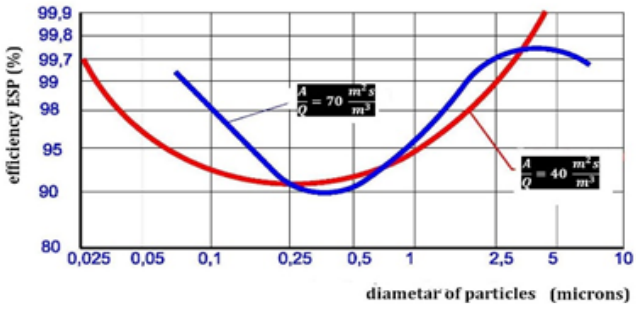


Figure 6: Fractional collection efficiency

The lowest collection efficiency is for particles with a diameter of 0.1-1 *μm*. The collection efficiency of very small particle diameters < 0.1 *μm* is very high, because their migration rate is proportional to C_m. This is an important feature of the electrostatic filter that will serve to extract fine particles. Removal of large particles is very efficient because migration velocity is proportional to the particle diameter.

2. CONDITIONING FLUE GAS

In order for the electrostatic filter to work efficiently and achieve low particle emissions with low power consumption, flue gas conditioning is often a good solution. The most common objective of conditioning is to reduce the electrical resistance of gas particles or to increase their cohesiveness. There are solutions for the conditioning of flue gases using the following additives:

- Add moisture: The most commonly used is the water inlet upstream of the electrostatic filter. The purpose is twofold: to reduce the gas temperature and to increase the humidity of the gas. Both of these effects reduce the electrical resistance of the ash particles in virtually all temperature ranges.
- Injection SO_3: Injecting SO_3 into flue gases reduces the electrical resistance of the particles. Low level of sulphur in coal is often caused by high ash resin resistance. The size of the electrostatic filter may in some cases be half the size of the non-conditioning filter [7].
- Injecting NH_3 (ammonia): Injecting NH_3 as a gas improves the performance of an electrostatic filter in a large number of cases, when the electrical resistance of particles is high. The conditioning effect by this process is lower in relation to the conditioning process with SO_3 [1].

This coal and biomass (wood sawdust) experiment showed that by adding biomass to a specific ratio in the charcoal mixture, it obtained a favourable composition of flue gases for the purpose of separating solid particles, respectively it was shown as a conditioning measure by adding to the furnace.

3. ELECTROSTATIC FILTER IN TPP "KAKANJ"

Previous expert analyses and experiences have shown that there are several causes of reduced collection efficiency of the electrostatic filter on Unit 5, namely:

- Insufficient electrostatic filter capacity for all the coalused in the conditions of exploitation,
- Insufficient efficiency of mechanical shaking of precipitation electrodes in the last fields,
- An unequal redistribution of flue gas through the left and right electrostatic filter fields,
- Deviation of working parameters of coal and ash from projected (moisture content, burnable ash content, flue gas temperature, coal quality ...).

To reduce the emission of particles from flue gases, the decision was made to build a sack filter. Now for the filtrate of flue gas on Unit 5 in TPP "Kakanj", it serves the socalled hybrid filter consisting of an earlier built electrostatic filter, and a subsequently built bag filter, Figure 7. They are installed in series and in the direction of flue gas flow. The electrostatic filter consists of two sections mounted on the left and right flue tract. Each section has four fields that have their own HV-rectifiers.

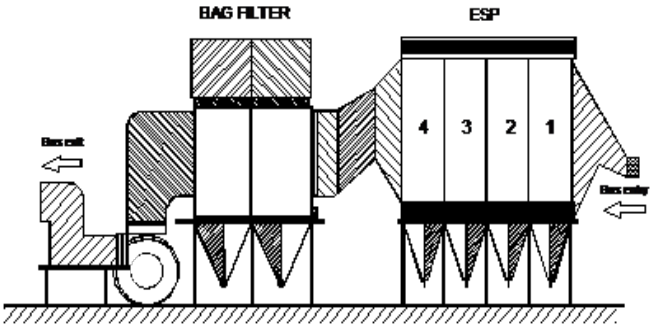


Figure 7: Hybrid filter to Unit 5

Operating parameters and basic technical characteristics of the electrostatic filters are:

-the temperature of the flue gas	170-2000^{O}C
-moisture content in flue gas	15%
-particle contents at the entrance	72.0 g/Nm^3
-particle contents at the exit	<0.150g/Nm^3
-electrical resistance of ash	> 5 x10^{10} Ωcm
-number of following fields	2x4
-medium velocity of flue gas	1.2 m/s
-average retention time	8.7 s
-area of collecting electrode	2x6,000 m^2
-secondary voltage(HV)	55 kV

4. BEHAVIOUR OF ELECTROSTATIC FILTER

The period of observation of the electrostatic filter behaviour during the combustion experiment is divided into two parts:

- coal combustion campaign, 27.03. – 01.04, and
- coal and biomass combustion campaign, 04.04–12.04.

To observe the behaviour of the electrostatic filter, the following data was used:

- power (MW) of Unit 5 and flue gas temperature on the flue gas duct,
- current and voltage of the HV-rectifier in the electrostatic filter fields,
- content of coal, biomass, and mixture "93% coal -7% biomass",
- the ash content of the electrostatic filter in the coal combustion campaign in fractions 100% (only coal), and combustion campaign in mixture "93% coal - 7% biomass",
- solid particles emission on the flue gas duct after the hybrid filter in the coal combustion campaign and combustion campaign in mixture "93% coal -7% biomass".

4.1. Results

It has been shown that there is no significant difference in flue gas temperatures during both parts of the experimental period, Figure 8.

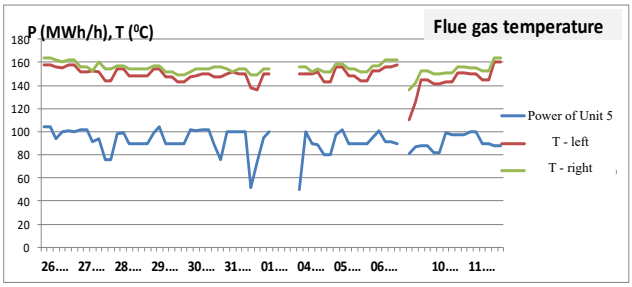


Figure 8: Flue gas temperature

The voltage values of the HV-rectifier in the electrostatic filter fields are shown in Figure 9.



Figure 9: HV-rectifier voltage values

The values of the HV-rectifier current in the electrostatic filter fields are shown in Figure 10.

These values were taken into account only in periods when the generator was synchronized with the network. That is why there is a time discontinuity of graph characteristics, which separates the coal burning campaign and the coal and biomass co-combustion campaign.

The fuel content in the experiment campaigns is shown in Table I.

The ash content of the electrostatic filter in the experiment campaigns is shown in Table II.

The solid particles emission measured on the flue gas duct after the hybrid filter is shown in Table III.

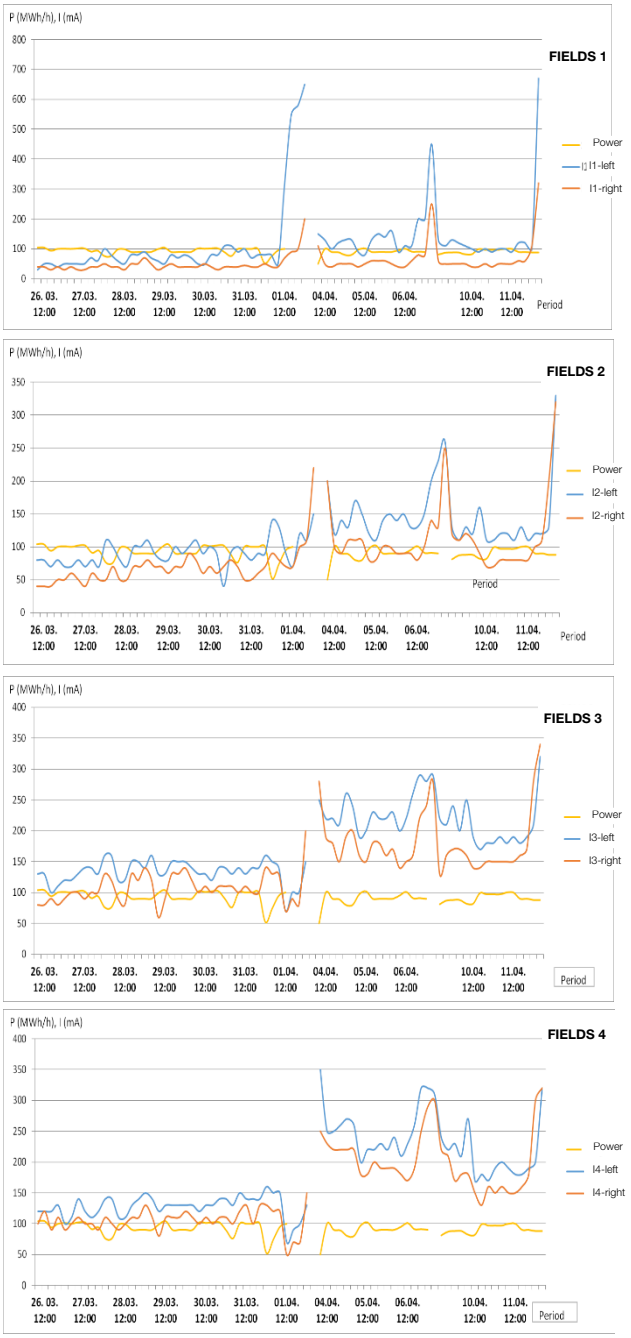


Figure 10: HV-rectifie rcurrent values

Table I: Fuel content in experiment campaigns [8]

CONTENTS OF FUEL	Unit	Coal 100%	Biomass 100%	Coal 93% Biomass 7%
Ash>10%	%m/m	44.00	-	40.35
Volatiles	%m/m	33.64	82.38	38.04
Combustible matter	%m/m	56.00	100	59.65
Coke	%m/m	66.36	-	61.96
Cfix	%m/m	22.36	17.62	22.69
Total carbon	%m/m	37.89	50.02	40.73
Hydrogen	%m/m	3.02	6.36	3.08
Nitrogen	%m/m	0.83	0.21	0.92
Oxygen	%m/m	11.87	43.24	12.9
Upper heat value	kJ/kg	15,506	19,992	16,414
Lower heat value	kJ/kg	14,884	18,725	15,780
Sulphur total	%m/m	2.39	-	1.94
Sulphur in ashes	%m/m	1.70	-	1.15
Sulphur flammable	%m/m	0.69	-	0.79

Table II: The content of ash below ESP during the experiment [8]

CONTENTS OF ASH	Unit	Coal 100%	Coal 93% Biomass 7%
SiO2	%m/m	49.020	44.880
Fe2O3	%m/m	8.980	9.180
Al2O3	%m/m	18.560	20.940
CaO	%m/m	14.720	15.860
MgO	%m/m	1.600	2.240
SO3	%m/m	1.390	1.900
TiO2	%m/m	0.25	0.250
NaO	%m/m	1.531	2.337
K2O	%m/m	1.345	0.755

Table III: Solid particles emission during the experiment [8]

Campaigns	mg/Nm^3
Coal 100%	18
Coal 93% - Biomass 7%	10

4.2. Comments

Graph of the flue gas and power of Unit 5 during the experiment, Figure 8, show that there was no change in the temperature of the flue gas during combustion and that it did not affect the collecting efficiency of electrostatic filter. The voltage graphs, Figure 9, show that the rectifier voltages did not change significantly in combustion campaigns. This shows that the power of the HV-rectifier was sufficient to keep the voltage even under the conditions of increased current load.

Current Graphs, Figure 10, show:

- That in the first fields of the electrostatic filter there were very small changes of current in the experiment campaigns. In the first fields, most large particles are separated by the electric charge generated by the electric field. HV-rectifiers of these fields work at maximum current load in both campaigns, and shaking electrodes is more frequent due to rapid deposition of particles.
- That in the second, third and fourth fields of the electrostatic filter, significant current differences in the biomass combustion campaign compared to the coal combustion campaign. It is seen that the second fields have an increase in current of about 50%, the third have a current increase of up to 100%, and finally, the fourth fields have an increase of more than 200% compared to the current for burning coal. In the last field of the electrostatic filter, fine particles of dust are deposited, which are more difficult to form an electrical charge. Therefore, this increase in the rectifier current may indicate that coal biomass generates favourable conditions for separating and fine particles of dust.

Table I shows the fuel content in experiment campaigns. It is seen that coal and biomass are contained in the content of a smaller ash content, the heat value is increased.

Table II shows the content of electrostatic filter ash in experiment campaigns. SO_2 content is seen to be reduced in the grinding campaign and SO_3 increased - which is advantageous from the aspect of particle removal.

Finally, Table III shows the average emissions of solid particles from flue gas after they leave electrostatic filter and then a hybrid filter. In the co-combustion of coal and biomass, solid particles emissions amounted to 10 mg/Nm^3, while in the combustion campaign only coal amounted to 18 mg/Nm^3.

5. CONCLUSION

This experiment demonstrates the positive effects of biomass combustion to increase the collection efficiency of the electrostatic filter. Improvements are particularly noticeable when separating fine particles of dust in the last fields of electrostatic filter.

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