Effect of electrostatic precipitation and agglomeration of particles on bag filter regeneration

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Abstract

Performances of a novel hybrid electrostatic filtration system HYBRYDA+ have been investigated in the paper. The semi-industrial scale hybrid system, of a flow rate of 6000 Nm^3/h, comprised of conventional electrostatic precipitator, kinematic electrostatic agglomerator and bag filter. The agglomeration process in this unipolar agglomerator was due to the collision between larger particles and smaller ones in the AC electric field. The electrostatic precipitator and kinematic electrostatic agglomerator used upstream of bag filter resulted in higher collection efficiency of the system than a bag filter operating alone, and the frequency of bag filter regeneration has been reduced. The period of bag filter regeneration without electrostatic agglomerator was about 8 minutes, but it increased more than 20 times, to 165 minutes, when the electrostatic precipitator and agglomerator were in operation. The collection efficiency of this system was >99.998%. The combination of electrostatic precipitator and agglomerator mitigate also the problem of bag filter clogging by submicron particles, which are agglomerated with larger particles (>5 μm) in the process of agglomeration.

Keywords
industrial gas cleaning, electrostatic precipitation, electrostatic agglomeration, hybrid filter,

1 Introduction

Precipitation of PM2.5 particles with high efficiency from exhausts still remains a challenge for environmental engineers. Mass collection efficiency of gas-cleaning devices commonly used in industry, for example, cyclones, scrubbers, electrostatic precipitators or bag filters, is usually higher than 99.9% for particles >2.5 µm. However, their performances for PM2.5 particles are insufficient to meet more stringent regulations. The interest in removal of PM2.5 and PM1 particles is increasing in recent years because the concentration of heavy metals and PAHs in these particles is higher than in larger ones. The collection efficiency for these particles can be increased by using hybrid systems, which combine various gas cleaning methods in one single device [1]. Further improvement in the collection efficiency can be obtained by using the process of particles agglomeration [2,3]. The agglomerated particles can be easier removed by the same conventional devices, but with higher collection efficiency than primary fine particles.

The solution developed in this paper combines conventional electrostatic precipitator and bag filter with a newly designed kinematic electrostatic agglomerator to a hybrid system, HYBRYDA+. High efficiency of particle removal by a bag filter requires frequent filter regeneration due to the clogging of the bag-filter pores. The regeneration of bag filters is done when the pressure drop across the filter exceeds a certain value. However, too frequent bag stressing lead to premature bag failure. Besides, more energy is required for air compression, and back pressure causes an increased emission of particle for a few seconds after each regeneration cycle. For this reason, the time between consecutive dislodging cycles should be as long as possible. The regeneration cycle of bag filter can be increased by two ways: by initial precipitation of particles by another method, for example, using electrostatic precipitator, and/or by the agglomeration of PM2.5 particles in order to prevent clogging the filter pores.

The paper presents results of experimental investigations of the effect of electrostatic precipitation and agglomeration of particles on bag filter regeneration in hybrid system HYBRYDA+. The hybrid system was tested at a semi-industrial scale installation downstream of a coal-fired boiler OP-650 (RAFAKO, Poland) of 225 MW power unit in a power plant South Poland. The flow rate through this experimental system was in the range of 3000-7500 Nm^3/h (about 2% of the total amount of exhaust gas produced by the boiler), and was controlled by a fan. The filter bags were regenerated by reverse air jet pulses. The resistivity of fly ash was about $3 \cdot 10^9$ Ohm·cm at 140° C and $7 \cdot 10^{10}$ Ohm·cm at 160° for 1st stage.

2 Hybrid electrostatic filtration system

A schematic of exhaust gas installation with hybrid electrostatic filtration system is shown in Figure 1. This system consists of three stages: electrostatic precipitator, electrostatic agglomerator, and bag filter. The electrostatic precipitator predominantly removes coarse particles (>20 µm) from the gas flow. The medium size particles (5-20 µm) and smaller, which are not precipitated, flow to the agglomerator stage in which PM2.5 particles are agglomerated in an alternating electric field with those of the medium size. Then, the agglomerates are directed towards the bottom of the bag filter chamber, in which they flow upwards through the bags, and are deposited onto the outer side of the bag filter. The cleaned gas returns to the main channel of the flue gas to the electrostatic precipitator and the stack.

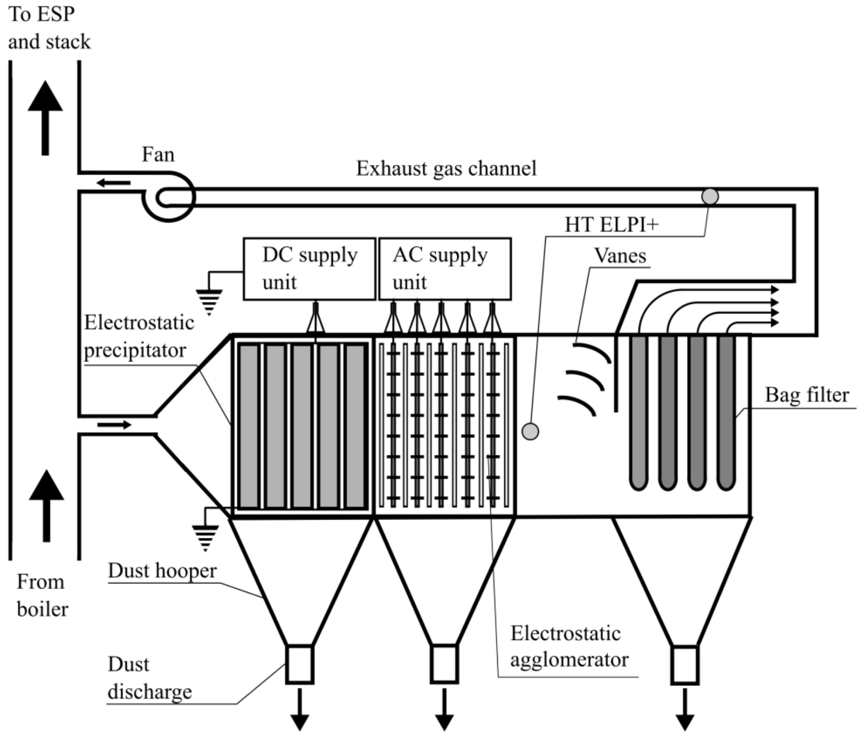


Fig 1. Schematic of hybrid electrostatic filtration system HYBRYDA+ with electrostatic precipitator, electrostatic agglomerator and bag filter.

Electrostatic precipitator used in the hybrid system consisted of five collecting and four discharge electrodes placed alternately. The height of the discharge electrodes was 2.2 m and their length about 2.8 m. The discharge electrodes were made in the form of rectangular frames with 10 spiked rods containing 19 discharge point. The diameter of each rod was 25 mm. Modupower TM MP 83-360 (Schenck Process, Norway) high voltage supply, with maximum output voltage of 83 kV of negative polarity and maximum load current of 360 mA, was used for discharge electrodes energization.

The second stage of hybrid system was the electrostatic agglomerator, which consisted of four discharge electrodes and three pairs of grids between them. The height of the discharge electrodes of electrostatic agglomerator was about 2.5 m and their length 2.6 m. The discharge electrodes, similar to electrostatic precipitator, were made in the form of rectangular frames, with 11 spiked rods of a diameter of 25 mm, which had 38 discharge points. The frames of grid electrodes of height of about 2.2 m and length 2.9 m consisted of 23 smooth rods. The diameter of each rod forming the grid was 25 mm. Additionally, grounded collection electrodes were mounted near the chamber walls, between the grid and wall, in order to reduce penetration of particles through the agglomerator in regions where agglomeration would be inefficient.

Electrodes of this agglomerator were supplied from a four-channel high voltage power supply unit, model ALWN-05/45-20, manufactured by ALGA (Poland), generating trapezoidal waveforms with controlled high voltage amplitude and signal frequency. The maximum amplitude of high voltage was 45 kV and signal frequency can be changed in the range from 10 to 100 Hz. The maximum load current was 20 mA.

Schematically, the voltage waveforms at outputs of the four-channel high voltage power supply unit and the set of electrodes are shown in Figure 2.

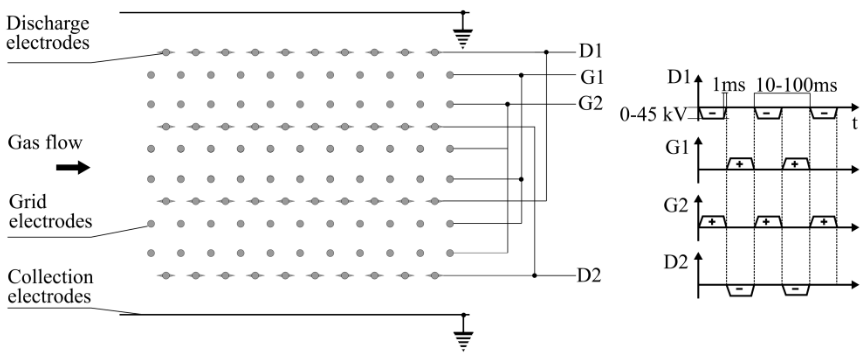


Fig 2. Schematic of electrodes configuration of electrostatic agglomeration and voltage waveforms generated by four-channel high voltage power supply.

In this type of electrostatic agglomerator, the ion current emitted by the discharge electrodes at negative potential in each half-period of supply voltage, flows through the adjacent grids, which are at the ground potential, and through the charging zone between the grids, towards the opposite grids at positive potential (cf. Fig.2). The potential of the grids and discharge electrodes alternately changes in each half-period of supply voltage. Particles flowing through the charging zone are electrically charged and left the agglomerator as charged particles. Due to the alternating electric field, larger particles oscillate with a greater amplitude than smaller particles with smaller charge. Due to this oscillatory motion, they collide with smaller particles, which are deposited on the larger once after collision.

The agglomeration process can be illustrated on the example of the movement of dust particles of various sizes in an alternating electric field. Particle trajectories and the oscillation amplitude for various particle sizes (taking into account the aerodynamic drag force, the external force of the electric field and the force of gravity) can be determined from the following equation of motion:

$$m_p \frac{d(\boldsymbol{v_p})}{dt} = \boldsymbol{F_D} + \boldsymbol{F_{Ext}} + \boldsymbol{F_g} \tag{1}$$

where F_D is drag force (with the Cunningham slip correction factor taken into consideration), F_{Ext} is the force of the electric field, and F_g is the force of gravity.

Large particles (5-20 µm) have a much larger oscillation amplitude, even two orders of magnitude greater than the PM2.5, depending on the surface charge density and particle size, by the same gaseous parameters and the same electric field. During these oscillations, the large particles "collect" smaller particles, creating larger and larger agglomerates [4].

The charge of particles may be estimated using the rate of charging equations determined by Arendt and Kallmann, and Pauthenier, for diffusion and field charging, respectively [5]:

$$\frac{d}{dt} Q_p \left[1 + \frac{\pi\epsilon_0 < v_i > {d_p}^2}{4 b_i Q_p}\right] = \frac{\pi}{4} e n_i \langle v_i \rangle {d_p}^2 exp\left(-\frac{e Q_p}{2\pi\epsilon_0 {d_p}^2 kT}\right) \tag{2}$$

$$\frac{d}{dt} Q_p = \frac{3}{4}\pi n_i e b_i E {d_p}^2 \frac{\varepsilon_r}{\varepsilon_r + 2}\left[1 - \frac{Q_p(\varepsilon_r + 2)}{3\pi\varepsilon_0\varepsilon_r E {d_p}^2}\right]^2 \tag{3}$$

where Q_p is the charge on particle, t is the time, ε_0 is vacuum permittivity, $<v_i>$ is the mean velocity of gaseous ions due to thermal motion, d_p is the diameter of spherical particle, b_i is the gaseous ions mobility, e is the elementary charge, n_i is the concentration of gaseous ions in the charging zone, k is the Boltzmann's constant, T is the absolute gas temperature, E is the magnitude of electric field, and ε_r is the dielectric constant of the particle.

The diffusion charging, main mechanism of nanoparticles charging, is dependent on gaseous ion concentration and gas temperature. The field charging is only a function of the electric field. It is usually assumed that the total charge of a particle is the sum of charges due to these two mechanisms operating independently.

The agglomerate of particles charged to the same sign is stable when the van der Waals force and the liquid-bride forces between the aggregated particles overcomes the Coulomb repulsion force.

The last stage of the hybrid filter is the bag house consisting of a set of 90 PTFE bags, type RK P84 (Remark-Kayser, Poland), approximately 3 meters long and 150 mm in diameter. The bags' yarns were coated with water- and oil-proof agent, and subjected to anti-static treatment. The air/cloth ratio was about 2 cm/s at the level of exhaust gases flow rate about 11 000 Am^3/h.

3 Experimental methodology

The size distribution of fly ash particles was measured by electrical low-pressure cascade impactor HT ELPI+ (DEKATI, Finland). The cut-off diameter (median size of particles), collected by each stage of impactor at a temperature of 140°C, is 7.2 nm, 11.5 nm, 22.8 nm, 41 nm, 76.1 nm, 136 nm, 238 nm, 368 nm, 597 nm, 955 μm, 1.7 μm, 2.5 μm, 3.8 μm, and 5.6 μm, for the 1st to 14th stage, respectively. Larger particles (>10 μm) are collected at the pre-separator stage (No. 15) at the inlet to cascade impactor, and were not analyzed.

Fly ash particles were sampled using the isokinetic probes at two locations of the installation for their concentration and size distribution measurement (cf. Fig. 1): downstream of the agglomerator and after bag filter (at the hybrid system outlet). The mass collection efficiency of the hybrid system has been determined by the on/off method by switching on or off the voltage of electrostatic precipitator and/or the voltage of electrostatic agglomerator (ESP ON, AGGL ON, ESP+AGGL ON, respectively). This procedure was used before and after bag filter regeneration.

The electric charge on fly ash particles downstream of the agglomerator was measured using the HT ELPI+, by the particle charger at the impactor inlet switched off.

The morphology of fly ash particles after agglomeration, collected downstream of the electrostatic agglomerator, was analyzed under scanning electron microscope EVO40 (ZEISS, Germany). The particles were collected onto copper targets, coated with high vacuum grease (Apiezon) in order to increase their adhesion to the target.

The dust was dislodged from the bag filter by air injected with a pressure of 0.6 MPa for a time of about 200 ms. The average regeneration period was obtained by measuring average time between consecutive dislodging.

4 Measurements

The magnitude of voltage and time averaged currents flowing to the electrodes of agglomerator were measured by the power supply unit ALWN-05/45-20. The current-voltage characteristics of the agglomerator measured for exhaust gas flowing with a flow rate of about 6000 Nm^3/h, for a frequency of supply voltage of 50 Hz, are presented in Figure 3. The gas temperature in the agglomerator chamber was 158°C. The maximal discharge current before breakdown was about 9 mA at a voltage of 40 kV when the electrodes were clean (dust free). For contaminated electrodes, the maximum of the discharge current before breakdown was 7.5 mA at 38 kV. The corona onset voltage was about 22.7 kV.

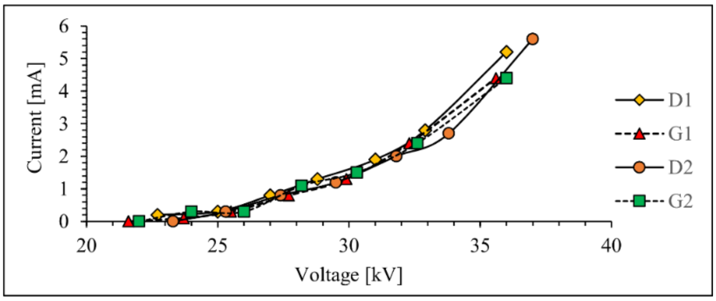


Fig 3. Current-voltage characteristics of electrostatic agglomerator for discharge electrodes (D1 and D2) and grid electrodes (G1 and G2)

4.1 Electrostatic precipitation and agglomeration effect on particle penetration

The exhaust gas flow rate during the measurements was of about 6000 Nm^3/h, and gas temperature downstream of agglomerator was about 160ºC.

The fractional size distribution of particles downstream of agglomerator is presented in Figure 4. By electrostatic precipitator operation (ESP ON), the number concentration of particles downstream the agglomerator decreased by about one order of magnitude. Slight decrease of concentration was also obtained after switching on the voltage of electrostatic agglomerator (ESP+AGGL ON). The mass concentration of particles measured at the electrostatic agglomerator outlet for PM10, PM2.5, PM1 particles is shown in Figure 5. Switching on individual devices resulted in decrease in all classes of particles to about the same level of concentration. The mass collection efficiency for electrostatic precipitator and agglomerator switched on was about 96% and 93% for PM10 and PM1, respectively (Table 1).

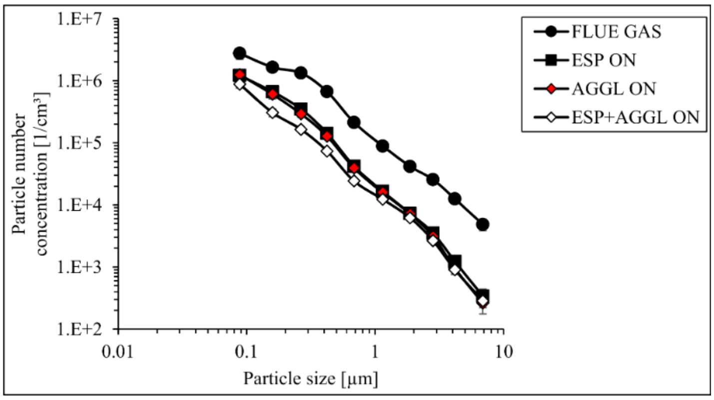


Fig 4. Fractional number concentration of particles downstream of electrostatic agglomerator for the following experimental conditions: raw flue gas (FLUE GAS), electrostatic precipitator

switched on (ESP ON), electrostatic agglomerator switched on (AGGL ON) and electrostatic precipitator and agglomerator switched on (ESP+AGGL ON). Supply voltage of electrostatic agglomerator and precipitator was 32 kV and 57 kV, respectively.

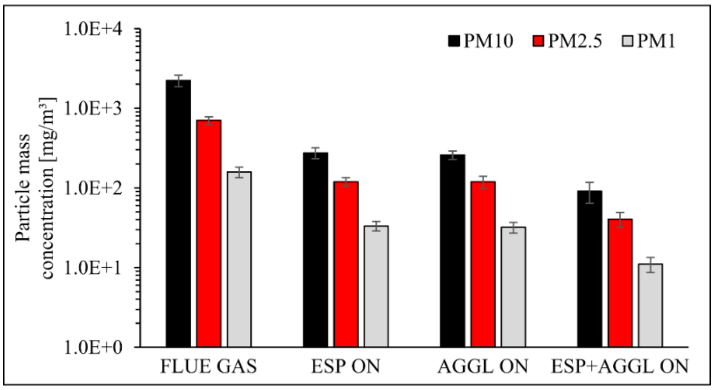


Fig 5. Mass concentration of particles in PM10, PM2.5 and PM1 downstream of electrostatic agglomerator for the following experimental conditions: raw flue gas (FLUE GAS), electrostatic precipitator switched on (ESP ON), electrostatic agglomerator switched on (AGGL ON) and electrostatic precipitator and agglomerator switched on (ESP+AGGL ON). Supply voltage of electrostatic agglomerator and precipitator was 32 kV and 57 kV, respectively.

Table 1. Mass collection efficiency for electrostatic precipitator and agglomerator switched off (FLUE GAS), electrostatic precipitator switched on (ESP ON), electrostatic agglomerator switched on (AGGL ON) and electrostatic precipitator and agglomerator switched on (ESP+AGGL ON) for PM10, PM2.5 and PM1 particles.

ON	PM10	PM2.5	PM1
ESP	87.66	82.95	78.97
AGGL	88.39	83.05	79.78
ESP+AGGL	95.94	94.22	93.03

The penetration of particles through the electrostatic agglomerator is defined as the ratio of concentration of particles at the outlet of agglomerator, N_{out}, to the concentration at its inlet, N_{in}:

$$Penetration_{Out/In} = \frac{N_{out}}{N_{in}} \quad (4)$$

However, in practice, the ON/OFF penetration is used, when the concentration of particles is only measured at the outlet of agglomerator. In that case, the ON/OFF penetration is defined by Equation (5) as the ratio of the concentration of particles for supply voltage of the agglomerator "on" to the concentration by supply voltage "off":

$$Penetration_{ON/OFF} = \frac{N_{ON}}{N_{OFF}} \quad (5)$$

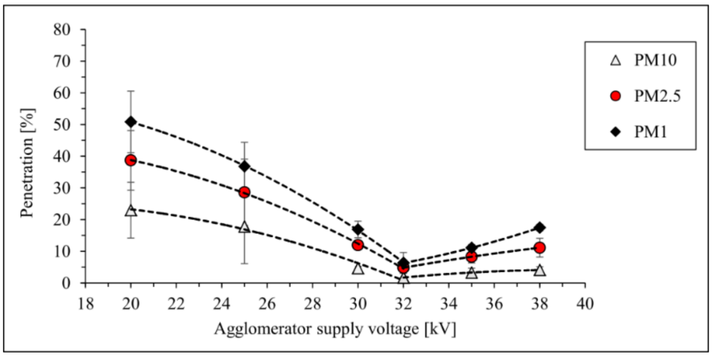


Fig 6. Particle penetration through electrostatic agglomerator vs. AC applied voltage

The particle penetration vs. AC voltage supplying agglomerator is shown in Figure 6. The penetration decreased from 20% to about 2% for PM10, with increasing AC voltage, until its magnitude was 32 kV. For smaller particles (PM2.5 and PM1), the penetration was higher, but the trend was the same: an increase in the applied voltage caused a decrease in particle penetration until the supply voltage was 32 kV. This effect means that the particles are precipitated on the agglomerator electrodes. For higher supply voltages, the penetration increased again. This phenomenon can be caused by re-entrainment of particles from the electrodes due to induction charging and/or spark discharge between the electrodes at higher voltages.

In order to learn about the morphology of particles leaving agglomerator, the samples of particles have been collected onto microscopic stage at the outlet of agglomerator. Examples of micrographs of fly ash particles taken under scanning electron microscope for switched off and switched on voltages supplying agglomerator are shown in Figure 7. Also a micrograph of fly ash particles collected on microscope stage for switched on the voltage supplying electrostatic precipitator is shown in Figure 7b. When the voltage supplying agglomerator was off, only small amount of particles was precipitated by the agglomerator and no agglomerates were obtained at the outlet. After switching on the voltage, almost all collected particles were agglomerates. Those agglomerates were in a form of a larger particle (of size of about 5-10 μm) with attached smaller particles of size <2 μm. For a supply voltage of agglomerator of 32 kV, the number of agglomerated particles was higher than for 30 kV (Figure 7c, d), what correlated with higher trend to decreased of penetration for PM1 than for PM2.5 or PM10 (cf. Figure 6). For switched on electrostatic precipitator (Fig. 7b) the agglomerates were observed in smaller number. This result supports the hypothesis that kinematic agglomeration, resulting from differences in particles' mobility, occurs in this type of agglomerator. Fig. 7e presents one of agglomerated particles obtained for supply voltage of 32 kV.

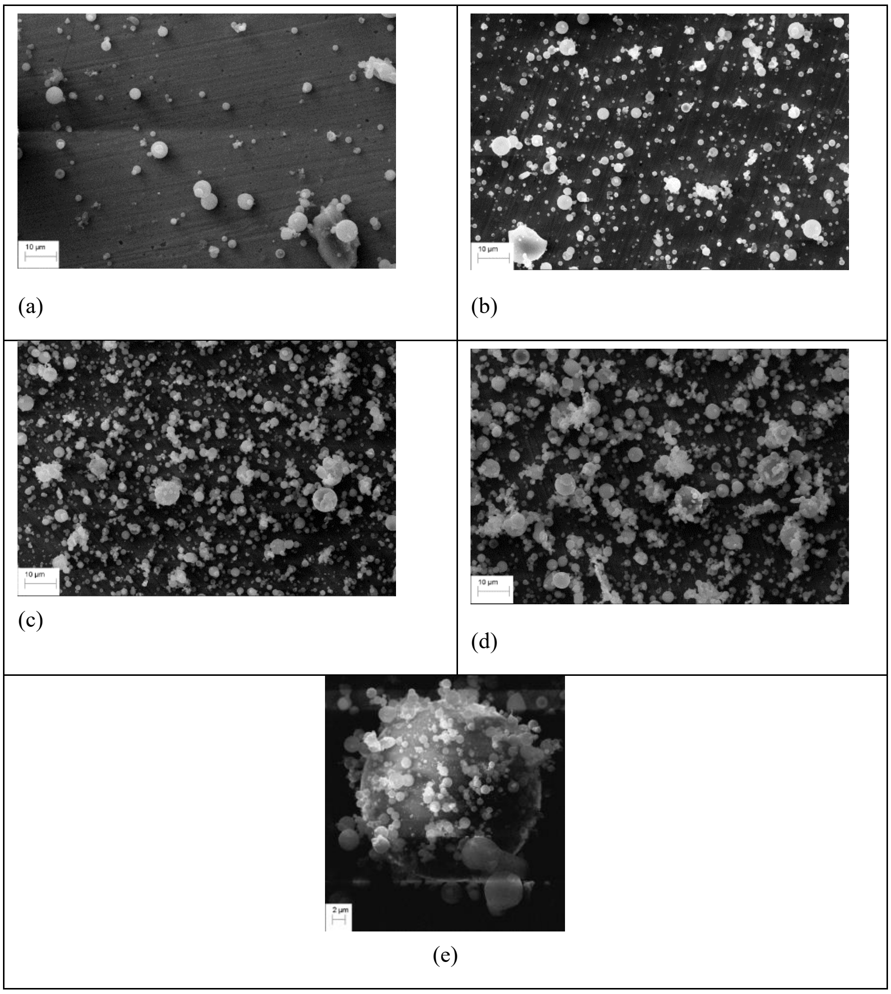


Fig 7. SEM images of fly ash particles deposited on microscopic stages at the outlet of electrostatic agglomerator, for the following experimental conditions: agglomerator voltage off (a), electrostatic precipitator voltage on (b), agglomerator voltage on of 30 kV (c),32 kV (d), and higher magnification of one of agglomerate obtained for supply voltage of 32 kV (e)

4.2 Electric charge of fly ash particles

The electric charge on particles leaving the agglomerator has been measured by the HT ELPI+ impactor. The results of measurement of mean charge on particles are presented in Fig. 8 for particles of size of 0.09, 1.1, 2.8 and 6.9 µm. The measurements were carried out for power unit load of 180 MW, flue gas flow rate about

6000 Nm^3/h through the hybrid system, and gas temperature of 161°C. The supply voltage of agglomerator was changed in the range from 25 to 34 kV. For the same supply voltage of agglomerator of 32 kV, the average charge of particles was about 17e, 205e, 1125e and 3860e for particles of mean size of 90 nm, 1.1, 2.8 and 6.9 µm, respectively. The theoretical value of the charge on particles of the same Stokes diameter, determined from the Pauthenier equation (3) and for diffusion charging (2), for the same experimental conditions is also drawn in this figure. The magnitude of charge only slightly increases with increasing supply voltage in the range from 28 kV to 34 kV that indicates the main mechanism of particle charging is the diffusion charging.

The difference between experimental and theoretical values for a voltage of 34 kV, for particles larger than 1 µm, results from the fact that highly charged particles can be precipitated in the agglomerator, particularly for higher voltages, and only particles of lower charges can leave the agglomerator, and can be measured by electrostatic impactor. For nanoparticles (90 nm) difference between measurement and theoretical values could result from underestimation of nanoparticles concentration during measurement of particle size distribution.

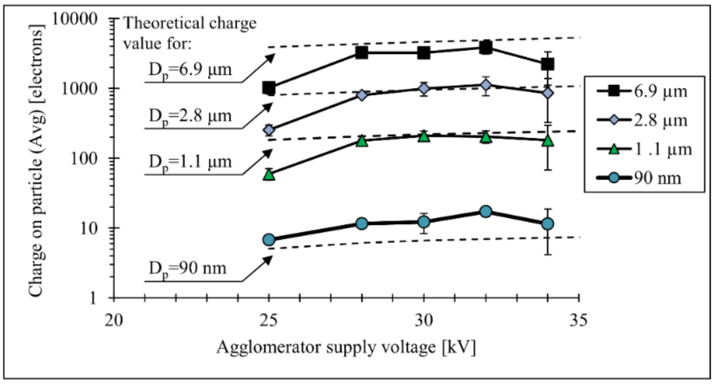


Fig 8. Mean value of electric charge on fly ash particles at the outlet of electrostatic agglomerator (in elementary charges e) depending on the voltage supplying the agglomerator, for particles of different mean Stokes diameter

4.3 Effect of electrostatic precipitator and agglomerator on filtration and bag filter regeneration

The fractional number concentration of particles in the size range between 6 nm and 10 µm measured in the outlet channel of HYBRYDA+ system (downstream of bag filter), is shown in Figure 9. The fractional number concentration decreases by about four orders of magnitude with increasing size of particles. After switching on the voltages of electrostatic precipitator and agglomerator (ESP+AGGL ON +BF) the total concentration decreases by about one order of magnitude.

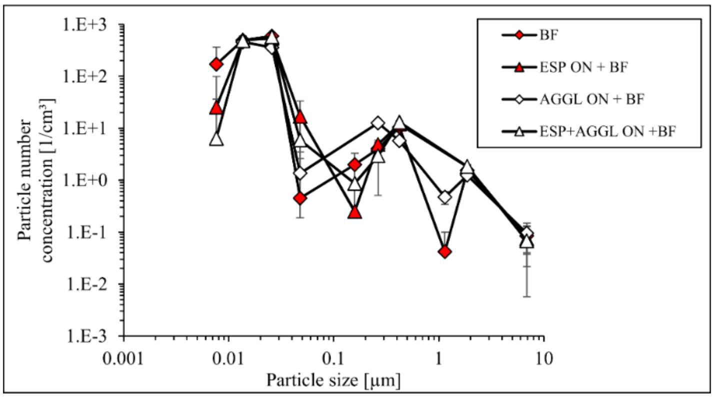


Fig 9. Fractional number concentration of particles at the outlet of HYBRYDA+ system for the following experimental conditions: electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator and agglomerator switched on (ESP+AGGL ON +BF), electrostatic precipitator switched on (ESP ON +BF), and electrostatic agglomerator switched on (AGGL ON +BF). Supply voltage of electrostatic agglomerator and precipitator were 32 kV and 57 kV, respectively.

The mass concentration of particles downstream of the bag filter for various classes of particles (PM10, PM2.5, PM1) is shown in Figure 10. The mass concentration did not change significantly after switching on electrostatic precipitator, agglomerator or electrostatic precipitator + agglomerator. The mass collection efficiency for all configurations of hybrid system is mainly determined by the collection efficiency of bag filter (Table 2). The mass collection was higher than 99.99 for all classes of particles. The role of electrostatic precipitator and electrostatic agglomerator is to remove coarse particles and agglomerate nanoparticles, and then reduce clogging of bag filter, and increase the regeneration period.

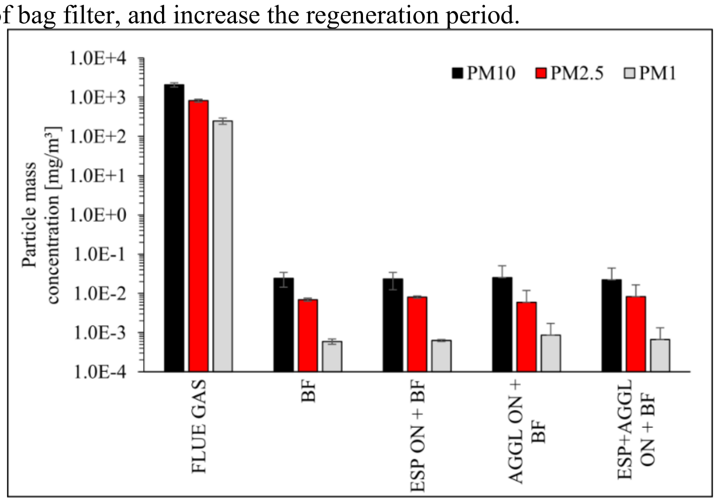
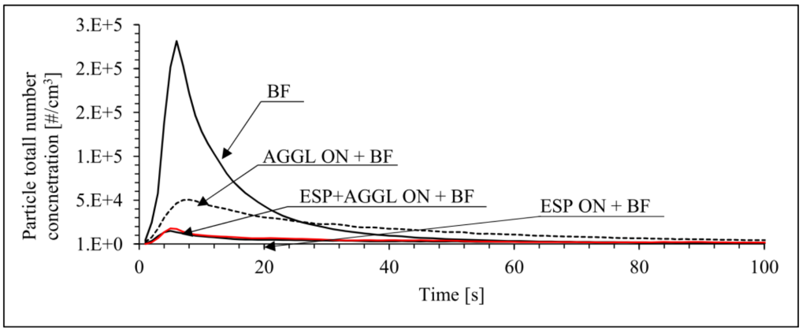


Fig 10. Mass concentration of particles at the hybrid system inlet (FLUE GAS), and downstream of the bag filter for various classes of particles determined for the following experimental conditions: for electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator switched on (ESP ON +BF), electrostatic agglomerator switched on (AGGL ON +BF), and electrostatic precipitator and agglomerator switched on (ESP+AGGL ON +BF). Supply voltages of electrostatic agglomerator and precipitator were 32 kV and 57 kV, respectively. The ash particle mass density = 1.2 g/cm3.

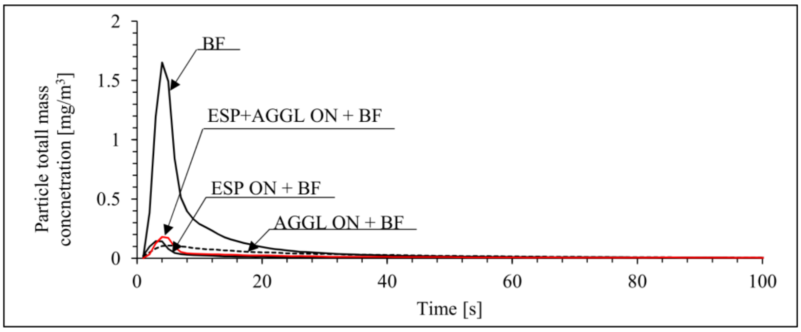
Table 2. Mass collection efficiency for PM10, PM2.5 and PM1 particles, for electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator switched on (ESP ON +BF), electrostatic agglomerator switched on (AGGL ON +BF) and electrostatic precipitator and agglomerator switched on (ESP+AGGL ON +BF). Supply voltages of electrostatic agglomerator and precipitator were 32 kV and 57 kV, respectively.

	PM10	PM2.5	PM1
BF	99.99884	99.99916	99.99976
ESP ON + BF	99.99888	99.99902	99.99975
AGGL ON + BF	99.99878	99.99928	99.99965
ESP+AGGL ON + BF	99.99894	99.999	99.99973

Time variations of the number and mass concentration of PM10 particles in the exhaust gas channel downstream of bag filter during air injection and after injection are shown in Figure 11. The dust emission during air injection is much higher when electrostatic precipitator and agglomerator are switched off. Switching on electrostatic precipitator or agglomerator decreases the number and mass concentration of particles at the system outlet during and after air injection. Switching on electrostatic precipitator and agglomerator did not reduce number and mass concentration of particles compared to only electrostatic precipitator switched on.



(a)



(b)

Fig 11. Particle total number (a) and mass (b) concentration of particles downstream of the bag filter during and after pulse-jet regeneration for the following combinations of operation: electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator and agglomerator switched on (ESP+AGGL ON + BF), electrostatic precipitator switched on (ESP ON + BF), and electrostatic agglomerator switched on (AGGL ON + BF). Supply voltage of electrostatic agglomerator and precipitator 32 kV and 57 kV, respectively.

Time variations of pressure drop across the bag filter is shown in Figure 12. The mean regeneration period of bag filter increases from about 8 min, for electrostatic precipitator and agglomerator switched off to 29 min when the voltages of electrostatic agglomerator is switched on (to 30 kV). Switched on electrostatic precipitator and agglomerator increased the time interval between air injection to about 200 min. Comparison of mean regeneration period and pressure drop across the dust cake for various supply voltages of agglomerator, for switched on electrostatic precipitator and switched on electrostatic precipitator and agglomerator is provided in Table 3. Increasing the supply voltage of agglomerator cause an increase of the time between two regenerations from about 500 s, for agglomerator switched off, to about 1760 s for 30 kV of supply voltage. Switching on electrostatic precipitator and agglomerator resulted in increased the mean time interval between two regenerations to 9946 s.

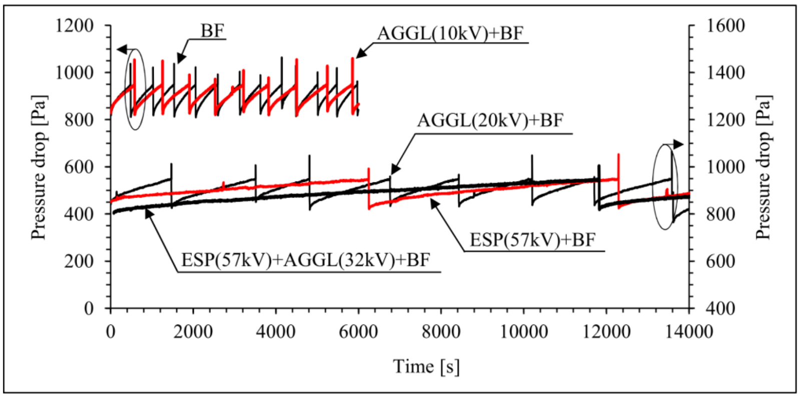


Fig 12. Time variations of pressure drops across the bag filter for the following experimental conditions: electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator and agglomerator switched on (ESP(57kV)+AGGL(32kV)+BF), electrostatic precipitator switched on (ESP(57kV)+BF), and electrostatic agglomerator switched on for 10 kV of supply voltage (AGGL(10kV)+BF) and 20 kV (AGGL(20kV)+BF)

Table 3. Comparison of regeneration period, total mass emission of fly ash particles after bag filter regeneration, and pressure drop across the dust cake for various combinations of switched on electrostatic precipitator and electrostatic agglomerator in the HYBRYDA+ system.

	Regeneration period [s]	Pressure drop across dust cake [Pa]
BF	497	20.1
BF+AGL(5 kV)	656	17.8
BF+AGL(10 kV)	715	17.4
BF+AGL(20 kV)	997	11.9
BF+AGL(30 kV)	1758	9.7
BF+ESP	5368	10.7
BF+ESP+AGL(32 kV)	9946	8.8

The average pressure drop after pulse-jet regeneration for various operation modes of hybrid system is shown in Figure 13. The results reveal that the pressure drop evolution is influenced by electrostatic precipitator and agglomerator. The pressure drop after regeneration is assumed to be the sum of the pressure drop across the clean filter and the pressure drop after dust cake rebuilt [6,7]. The pressure drop after rebuilding the dust cake should increase constantly until next pulse regeneration [8]. Given that the pressure drop across the clean filter is independent of the switched on of the electrostatic device, the difference between the pressure drop after rebuilding the dust cake should depend on its thickness and the particle size distribution forming the dust cake [9]. Switched on electrostatic agglomerator decreased the pressure drop on the dust cake and this pressure drop decreased with increasing agglomerator supply voltage. The lowest pressure drop was observed for switched on electrostatic precipitator and agglomerator.

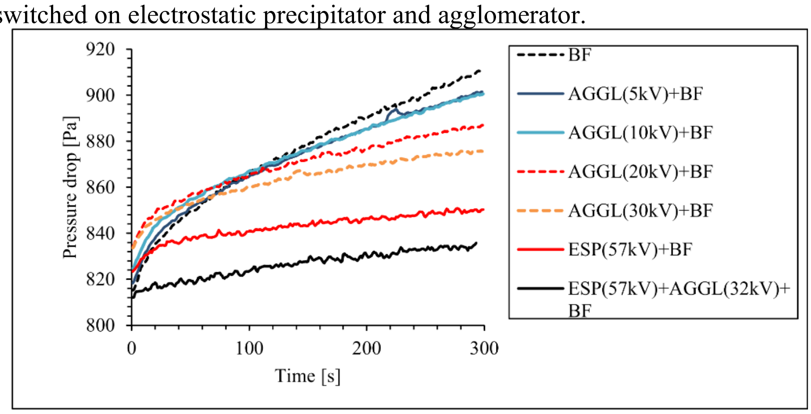


Fig 13. Pressure drops across the bag filter during the first 300 s after pulse-jet regeneration for the following experimental conditions: electrostatic precipitator and agglomerator switched off (BF), electrostatic precipitator and agglomerator switched on (ESP(57kV)+AGGL(32kV)+BF), electrostatic precipitator switched on (ESP(57kV)+BF), and electrostatic agglomerator switched on for 10 kV of supply voltage (AGGL(10kV)+BF) and 20 kV (AGGL(20kV)+BF)

5 Discussion

By using the electrostatic precipitator and electrostatic agglomerator the regeneration period of bag filter has been increased. Three effects are responsible for the longer regeneration time: electrostatic precipitation of dust particles, kinematic agglomeration by deposition PM2.5 particles on larger particles, and porous dust cake building by electrically charged particles.

Electrostatic precipitation process removes the most particles that results in slower dust cake building on the bag. The main advantage of the investigated hybrid system is that most of the largest fly ash particles are first precipitated by electrostatic precipitator. Another advantage is that submicron and nanoparticles are agglomerated with the larger ones in the electrostatic agglomerator, remain on these particles at the bag surface and do not penetrate the filter pores that could lead to clogging of the filter.

The use of an electrostatic precipitator before bag filter significantly extends the time between two regenerations. In the case of investigated system, the mean time between regenerations associated with a high efficiency in removing particles by the electrostatic precipitator (88%) increased more than 10 times. The addition of agglomerator after the ESP causes a twenty-fold increase in the time between regenerations, which is not proportional to the efficiency of removing particles by switched on electrostatic precipitator and agglomerator (95%). Longer regeneration time could be the effect of kinematic agglomeration

Effects of particles agglomeration was inspected under SEM. SEM micrographs of particle samples collected at the outlet of agglomerator stage showed that switching on the agglomerator resulted higher number of large particles with attached PM1 particles. The observed decrease in the penetration of PM1 particles with increasing supply voltage of the agglomerator cannot be explained by classical electrostatic precipitation only because the charge of these particles due to existing charging mechanism is insufficient for particles this size to be precipitated. The possible explanation is the mechanism of agglomeration, which remains the PM2.5 particles at the filter surface.

Additionally, the effect of charged particles was that the dust cake is more porous resulting in lower pressure drop after re-building dust cake. It is known from other papers that cake morphology at bag filter is different for uncharged and charged particles. The dust cake of charged particles is more fragile, which allows the particles to be more easily dislodged [9-12].

The porous structure of dust cake and particle "bridges" between the fibers built by charged particles, remain free space between them [13] that significantly reduces the pressure drop across the filter and increases the regeneration period. It was also noticed that the Coulomb repulsion due to the charge accumulated on the fibers decelerates the incident particles and decreases the apparent face velocity of these particles [14,15].

Using electrostatic precipitator and agglomerator in this system, the pressure drop decreased effectively up to 2 times less than for bag filter only.

6 Conclusions

The effect of electrostatic precipitator and electrostatic agglomerator on bag filter regeneration in hybrid system HYBRYDA+ has been investigated. The HYBRYDA+ system operated downstream of a coal-fired boiler of 225 MW power plant unit. The gas stream was sucked from the main exhaust duct to the hybrid system, and returned after precipitation to the same duct upstream of electrostatic precipitator operating in this power plant. In this kinematic electrostatic agglomerator the agglomeration process was due to collision between larger particles and smaller ones in AC electric field. The use of a kinematic electrostatic agglomerator downstream of electrostatic precipitator at the exhaust gas outlet resulted in reduction of frequency of bag filter regeneration. The collection efficiency of the bag filter alone was about 99.991%, but the bag regeneration period was about 8 minutes. Using electrostatic precipitator and electrostatic agglomerator allowed increasing the regeneration period of bag filter more than 20 times, i.e. to about 165 minutes, and the collection efficiency increased to 99.998%.

The combination of electrostatic precipitator and agglomerator should mitigate the problem of bag filter clogging by submicron particles and increase the regeneration period and live time of bag filter.

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