Part 1

AIR PROTECTION FROM POWER INDUSTRY EMISSIONS

1.2. Ash collecting at TPPs

1.2.2. Fly ash collecting technologies at TPPs

1.2.2.3. Electrostatic precipitators

Prokhorov V.B., MPEI (TU)

Electrostatic precipitators (ESPs) are the most widely applied at TPPs as ash collectors, since they allow to clean gases from ash with efficiency of 0,990 ... 0,998 at the hydraulic resistance of less than 200 Pa. Capital expenditures for construction of ESPs are high, as these devices are metal-intensive, require large space, are equipped with special stepping up-rectifier units of power supply.

An essence of the process of electric gas purification is as follows. In ESPs the dusty gas moves in the channels formed by collecting (precipitation) electrodes, between which discharge electrodes are located at some distance. High-voltage direct current (negative, as a rule) is supplied to the discharge electrodes, and the collecting electrodes are grounded. At certain electric field intensity, ionization of flue gases occurs. Ionization is accompanied by appearance of corona discharge, which isn't applied to the whole interelectrode gap and decays with decrease in electric field in the direction of the collecting electrode. Gas ions of different polarity, formed in the crown zone, under electric field impact move toward the oppositely charged electrodes, resulting in occurrence in the interelectrode space of electric current, called the corona current. Ash particles, adsorbing the ions, acquire an electric charge and under electric field move to the electrodes, precipitating at them. The basic amount of particles is deposited at the developed surface of the collecting electrodes, a smaller part of them goes to the discharge electrode. At regular intervals, with the striking mechanism the electrodes are shaken, and ash particles fall into the hopper under gravity.

Corona discharge occurs when the certain electric field intensity is reached, which is called a critical one. With increase in intension above the critical, corona current grows and ash collection efficiency is raising, as well. However, at further increase in the electric field intensity, a breakdown of the interelectrode space with spark or arc electric charge, occurs. Thus, for the electrical cleaning of flue gases it is necessary to meet:

$$E_{cr} < E > E_{pr}, \qquad (1.15)$$

where E_{cr}, E_{pr} is the critical and the breakdown electric field intensity.

In order to reduce capital costs and improve the ash collection efficiency, a design of ESPs is continuously being improved. Until 1980 ESPs of UG series (uniform horizontal) were the most widely applied, then ESPs of EGA, EGB, and EGV series were in use (horizontal ESPs of A, B and C modifications). Technical specifications of the mentioned above ESP types are listed in Table 1.9 [3]. As shown in Table 1.9, the main difference between these devices is a gradual increase in the interelectrode distance, which significantly reduces metal consumption of electrostatic precipitators.

Table 1.9. **Technical specifications of ESPs**

Index	ESP type				
	UG	EGA	EGB	EGV	EGD
Interelectrode distance, mm	275	300	350	460	300
Active electrode height, m	4; 7,5; 12	6; 7,5; 9; 12	6; 7,5; 9; 12	6; 7,5; 9; 12; 15	18
Active section, m^2	10...265	16...285	16...285	10...364	181...350
Performance at the conventional gas velocity of 1 m/s, thousand m^3 / h	36,0... 954,0	57,6... 1026,0	57,6... 1026,0	36,0... 1360,0	651,6... 1260,0
A number of electric fields	2—4	2—4	2—5	2—8	3—5
Maximum overall dimensions, m:					
height H	27,75	19,90	19,90	22,90	39,48
length L	24,80	22,74	22,74	48,60	31,105
width B	29,87	29,54	29,54	35,75	25,94
Nominal voltage of supply units, kV	80	80	80; 110	110	80

In Fig. 1.26 EGA precipitator, the most widespread in Russia, is shown. Flue gases after the distribution lattice enter the corridors, formed by vertically hanging broadband collecting electrodes. Collecting and discharge electrodes combine together along the gas path into the fields of 2,56 to 5,12 m long. Depending on the required degree of gas purification, a number of fields can be from two to five. Increasing the number of fields results in the ash collection efficiency grow, but it leads to increase in metal consumption, dimensions and cost of ESP. Collecting electrodes are drawn from the standard elements of 640 mm wide. A number of elements may vary from four to eight.

Currently, the most applied are collecting electrodes of the open profile. As the discharge electrodes a small-diameter wire (3 ... 5 mm) of the round or bayonet profile was previously used.

Nowadays discharge electrodes with the fixed discharge points, representing a barbed wire or thin-walled elements with the needles stamped from space to space, are used. In the notation of ESP of EGA type the following indicators are mentioned: a number of parallel sections, a number of gas passages between the collecting electrodes, a height of the electrodes, a number of elements in the collecting electrode, a number of fields. Thus, ESP EGA 2-56-12-6-4 means: horizontal electrostatic precipitator of A modification with two parallel sections, 56 gas passages, with the electrodes of 12 m high, six elements in the precipitation electrode and four fields set consecutively.

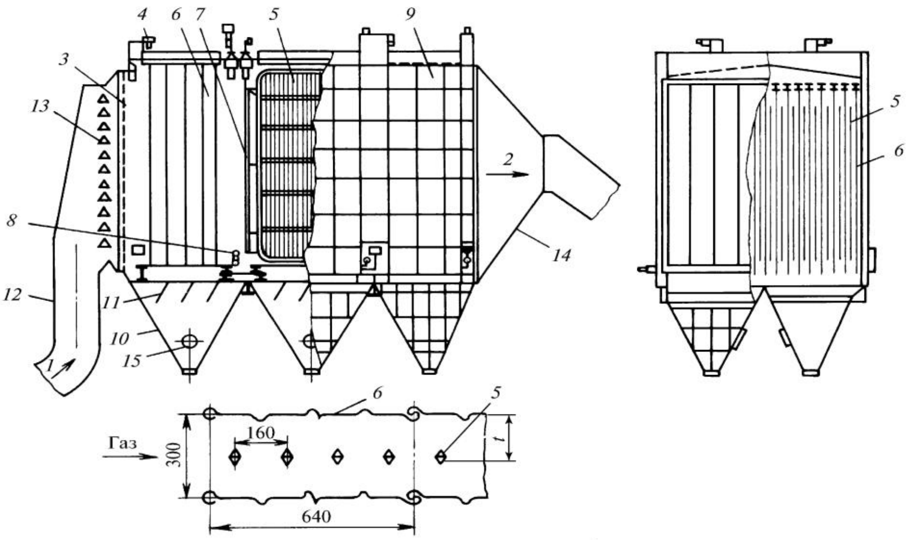


Fig. 1.26. **Three-field two-section electrostatic precipitator of EGA type:** 1 – inlet of the dusty gas; 2 – outlet of the purified gas, 3 – gas distribution grate, 4 – high-voltage current supply, 5 – corona electrode, 6 – collecting electrodes, 7 – shaking mechanism of the corona electrodes, 8 – shaking mechanism of the collecting electrodes, 9 – body; 10 – hopper, 11 – partitions (walls) to reduce the gas flows through the hopper, 12 – the lift shaft, 13 – gas distribution volume elements designed by MPEI, 14 – confusor flue gas discharge, 15 – inspection hatches in the hoppers; *t* - distance between the corona and collecting electrodes

ESP body is made of metal. Under each field of ESP a hopper for collecting the captured ash is installed. High-voltage electric current (60 ... 80 kW) to the ESP is supplied to power units. The power unit consists of a voltage regulator, step-up transformer and rectifier. To ensure an optimum supply mode, voltage at the electrodes should be maintained at the highest level, but below the breakdown. A process of voltage regulation at ESP electrodes is automatic. To regulate the output voltage and current, magnetic amplifiers and thyristors are applied. Power units are equipped with semiconductor rectifiers.

Let's transform the equation (1.6):

$$\Pi = vA/V = vf, \qquad (1.16)$$

where f is a specific surface of precipitation.

Thus, the ash collection parameter and efficiency is determined by two factors: the drift velocity and surface area of deposition. Increasing f, we obtain a high efficiency of ash collecting, but it is associated with the increased dimensions of ESP and raising its price.

The drift velocity is determined, mainly, by the electrical characteristics of ESP and dust-gas flow. A theoretical relationship for determination of the drift velocity, m/s, is as follows:

$$v = \frac{\varepsilon_0 E_3 E_{oc} d}{\mu} \frac{\varepsilon}{\varepsilon + 2}, \qquad (1.17)$$

where ε_0 is a permittivity of vacuum, F/m; ε – relative dielectric permittivity of particle matter, E_3 – electric field intensity, V/m; E_{oc} – electric field precipitation, V/m; μ — dynamic viscosity of gas, Pa s; d — diameter of ash particles, m; ε and μ of the dust and gas flow in ESPs are practically unchanged, so the ash collection parameter and efficiency depend on the intensity of electric field of charge and precipitation, and on the size of ash particles. Small ash particles are collected not as well as the larger ones. However, in ESPs fine ash particles are captured better, than in the inertial ones, in which the ash collecting parameter is proportional to the particle diameter in the second degree. It's complicated to determine E_3 и E_{oc} theoretically, and estimation of the drift velocity by equation (1.17) is possible only if there are experimental data relating to electrical characteristics.

The drift velocity in ESP much depends on the resistivity of ash ρ. In Fig. 1.27, *a* the change in drift velocity as a function of resistivity is shown. In the area of $\rho = 10^8 \ldots 10^9$ Ohm·m, a sharp drop in the drift velocity occurs, that is associated with formation of the "inverse crown".

An essence of this phenomenon lies in the fact that at the ash layer of high resistivity, precipitated at the collecting electrode, there is a large voltage drop, and in the gas gap its drop is reduced. A fall of the electrostatic field intensity results in the drift velocity reduction and ash collection efficiency decrease. In addition, in case of excess of some critical value of electric field intensity in the ash layer, breakdown of the porous layer occurs, resulting in formation of a thin channel, filled with positive ions. The channel serves as a point, from which the strong back corona discharge is developed, which acts towards the core. In the interelectrode space positively charged ions are released that neutralize the negatively charged ash particles, moving to the precipitation electrode, and ash collection efficiency sharply decreases.

Specific electric resistance of ash depends on the temperature and humidity of gases, chemical composition of flue gases. Micro-composition of some impurities can significantly influence the reduction of electrical resistance of ash (for example, SO_3 concentration).

To increase an efficiency of collecting the ash with a high electrical resistivity, a number of methods have been developed. In Fig. 1.27, *b* correlation between the ash resistivity and flue gas temperature is shown. From Fig. 1.27, *b* it could be seen that in a zone of the most typical flue gas temperature (t_{fl} = 140 ... 160°C), the maximum ash resistivity is observed. With increase or decrease in the temperature from these values, a reduction of the electrical resistance of ash occurs.

Using the right high-temperature branch of the characteristic is possible at installation of ESPs before the air heater in the flue gas temperature range of 350 ... 400°C. However, this route is not profitable due to significant increase in the volume flow rate of flue gases, which makes it necessary to increase ESP dimensions and complicates the design of its elements at high temperatures.

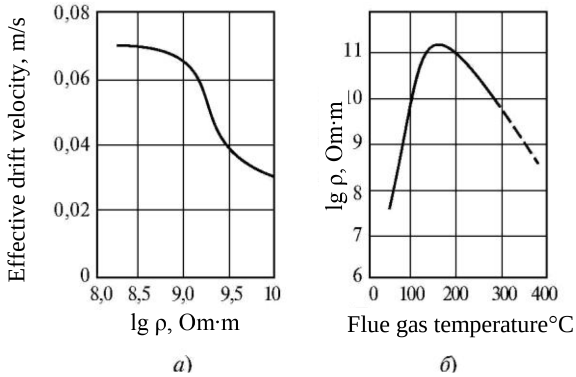


Fig. 1.27. **Influence of the dust and gas flow properties on operation of electrostatic precipitators (example - Ekibastuzsky coal)**: *a* — effective drift velocity vs the specific ash resistivity logarithm, *b* – $l_{g\rho}$ of ash vs the flue gas temperature

To reduce the electrical resistivity of ash, temperature and humidity conditioning of flue gases found its practical application, which can be carried out by installing a wet scrubber before the ESP, as well as due to water supply before the ESP, fed through special fine nozzles. Temperature and humidity conditioning of flue gases reduces a gas temperature to 80 ... 90°C. At that, moisture and various chemical substances, primarily, sulfur dioxide, are adsorbed by the ash surface. This leads to decrease in the electrical resistivity and raising the ash collecting efficiency. At application of this method it is very important to provide a fine spray of moisture throughout the volume of flue gases for its evaporation before entering the electrostatic precipitator. Otherwise, it will lead to the increased corrosion of ESP elements.

Another way to reduce the electrical resistivity of ash is the use of chemical conditioning of flue gases by microdoses of sulfur trioxide. Thus, when injecting SO_3 into flue gases in the amount of 20 ppm (20 particles per million by volume) the ash resistivity is reduced and can prevent from the inverse crown formation.

Despite of the chemical conditioning efficiency, this method isn't widespread in Russia, because of operational difficulties and costs, associated with obtaining and supplying of various aggressive substances into boiler.

Prevention from the inverse crown formation or reduction of its intensity could be realized by supply of impulse voltage to the electrodes and supply of ESP by voltage of alternating polarity. These methods are under experimental testing.

To increase the collecting efficiency of ash with high specific electrical resistivity, the reduced gas velocities in ESP are used. This increases the overall dimensions of ESP and growth of its price, but allows to compensate an adverse impact of the inverse corona. Thus, if for the traditional ash, gas velocity in ESP is in the range of 1,5 ... 1,8 m/s, than at a high electrical resistivity it is 1,0 ... 1,2 m/s.

Out of the most common in Russia coals, the high electrical resistivity of fly ash is observed in Ekibastuzsky and Kuznetsky coals.

The ash collecting efficiency is greatly influenced by the uniformity of velocity field distribution of flue gases through the ESP cross section, which can be estimated by a degree of ESP filling - *m*:

$$m = \frac{\left(\sum_{i=1}^{i=n} u_i\right)^2}{n \sum_{i=1}^{i=n} u_i^2}, \qquad (1.18)$$

where u_i is a gas velocity per the element of ESP area; n is a number of equal elementary areas in ESP cross section.

ESP filling degree *m* is defined at the study of aerodynamic characteristics of ESP model with the feeding and discharge ducts. The cross section of ESP model is divided into *n* equal areas, and in the center of each area velocity of the flow is measured.

m is directly related to the ash slip according to the equation:

$$P_a = P_p^{\,m}, \qquad (1.19)$$

where P_p is an ash slip through the ESP at a uniform velocity field; P_a is an ash slip at the velocity field with the degree of volume filling equal to *m*.

In addition to the degree of volume filling, to characterize the uniformity of velocity field distribution, an average velocity squared deviation from its mean value is sometimes used, which can be determined as follows:

$$\Delta\overline{u}^{2}_{av} = \frac{1}{n}\sum_{j=1}^{j=n} \Delta\overline{u_j^2}, \qquad (1.20)$$

where

$$\overline{u}_j^{\,2} = \left(\frac{u_j - u_p}{u_p}\right)^2; \qquad (1.21)$$

u_j and u_p are the gas velocity in *j* point and the gas velocity at the uniform velocity field, accordingly.

The ash slip through ESP is associated with the average velocity squared deviation from its mean value by the following expression:

$$P_a = (1 + R\Delta\overline{u}^{2}_{av})P_p \qquad (1.22)$$

where *R* is a factor, considering the increased influence of non-uniformity of gas velocity field, depending on the ash collecting efficiency,

$$R = 0{,}125(1 + \Pi_p)\Pi_p \qquad (1.23)$$

where Π_p is the ash collection parameter at the uniform velocity field.

An influence of *R* factor increases for ESPs with high ash collecting efficiency, therefore, to raise ESP efficiency it is necessary to ensure a maximum uniformity of the velocity field.

$\Delta\overline{u}^{2}_{av}$ can be estimated in terms of the degree of volume filling:

$$\Delta\overline{u}^{2}_{av} = \frac{1}{m} - 1 \qquad (1.24)$$

If no special measures are taken, then a large unevenness of velocity field in ESP will be observed. This is because the gas velocity in the boiler convective shaft is much higher than in ESP, so at ESP inlet a diffuser with large angles of opening should be installed, which leads to uneven distribution of the gas velocity over the cross section of ESP.

To improve the velocity field uniformity at ESP inlet volume and flat lattices are installed. In Fig. 1.28, *a* and *b* gas distribution devices at gas supply to ESP from the bottom and at direct supply are shown.

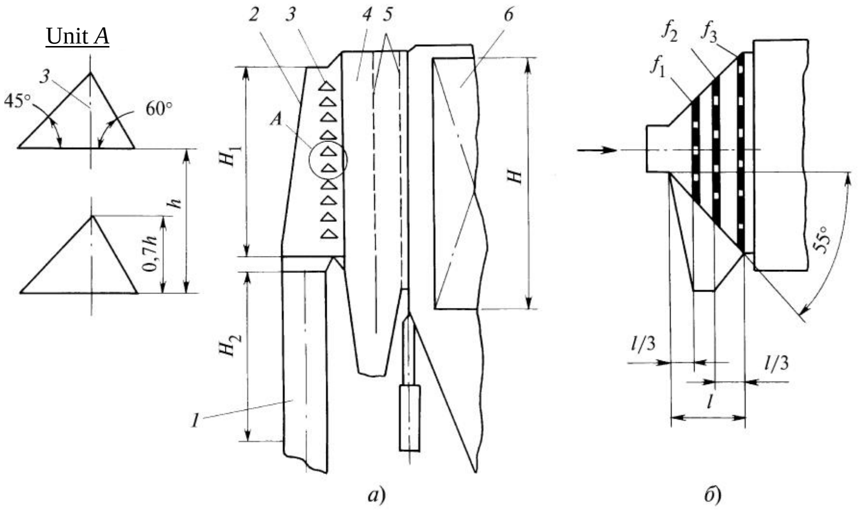


Fig. 1.28. Gas distribution units: *a* — gas distribution unit designed by MPEI for supplying gas from the bottom, where 1 is a lifting shaft, 2 - beveled part of the lift shafts, 3 - grid of volume elements, 4 – pre-chamber; 5 - flat perforated gas-distribution grids with effective cross sections f_1 = 0,7, f_2 = f_3 = 0,5; 6 - active ESP field, *b* - gas distribution unit with a diffuser at horizontal gas supply

When supplying gas to the precipitator from the bottom, gas distribution MPEI units are recommended, consisting of a vertical lift shaft of the constant cross section, one volume grid and two flat grids. The volume grid is set at the place of gas turning to ESP. Volume elements divide the entrance chamber by height into a number of horizontal channels, each representing a confuser, firstly, and then the diffuser. The lower channel walls (sides of the triangular elements) are made inclined to avoid accumulation of ash (angles at the triangle base are assumed to be 45° at the inlet and 60° at the outlet). To have the same gas flow rate through the channels formed by volume elements, the upper section of the lift shaft is performed with beveled front wall.

Table 1.10. **Input-to medium-volume ESP arithmetic mean values of squared deviation of the gas velocity for gas-distributing units with volume MPEI elements**

Relative height of the lifting shaft $l = H_2/H$	Single lattice			Two lattices		
	$\Delta \overline{u}^2_{in}$	$\Delta \overline{u}^2_{av}$ at a number of fields		$\Delta \overline{u}^2_{in}$	$\Delta \overline{u}^2_{av}$ at a number of fields	
		3	4		3	4
0	0,176	0,100	0,084	0,087	0,068	0,055
0,4	0,099	0,079	0,070	0,064	0,053	0,047
0,8	0,064	0,064	0,060	0,042	0,042	0,042

Living section of the volume lattice *f* is assumed to be 0,25 ... 0,35. After the volume lattice, the flow is directed horizontally and normally passes through two planar lattices. Each planar lattice has a living section of 0,5.

In case of direct supply of gas to ESP (Fig. 1.28, *b*) a diffuser with a moderate opening angle is used. Flat lattices (from one to three) are installed there. In Tabs. 1.10 and 1.11 arithmetic mean values of squared deviation of the gas velocity at the ESP inlet $\overline{u}^2_{in}$ and along the ESP volume $\overline{u}^2_{av}$ for the lower and direct gas supply to ESP are resulted.

Table 1.11. **Input-to medium-volume ESP arithmetic mean values of velocity squared deviation for diffuser gas-distributing units**

A number of lattices	$\Delta \overline{u}^2_{in}$	$\Delta \overline{u}^2_{av}$ at a number of fields	
		3	4
1	0,538	0,150	0,120
2	0,235	0,115	0,096

Reduction of ash collecting efficiency causes movement of dust and gas flow outside of active zones of the ESP. The main gas part is moving in the active zone of the ESP in a space between precipitation and discharge electrodes, which charging and precipitation of ash particles occur. However, a part of gases can move in semi-active and inactive areas of the precipitator. Inactive ESP zones are areas above the electrode system and under it (together with the dust collecting hoppers), as well as the gaps between outer precipitation electrodes and ESP body. In inactive zones the electric field intensity is absent and ash is not collected. The largest gas leakages occur through the bottom inactive ESP zone below the electrode system. Blind overlapping of inactive zones is not possible due to necessity of compliance with breakdown periods and maintaining clearance between the body and the electrodes for a normal shake.

In modern ESP designs the height of discharge electrodes is slightly less than of precipitation ones. An area, in which precipitation electrode exists and the discharge one is absent, has a weakened electric field and called semi-active. Ash slip in the ash semi-active zone is 2 ... 3 times higher than in the active.

Ash slip *P* through ESP taking into account gas leakages through the semi-active and inactive zones can be determined as follows

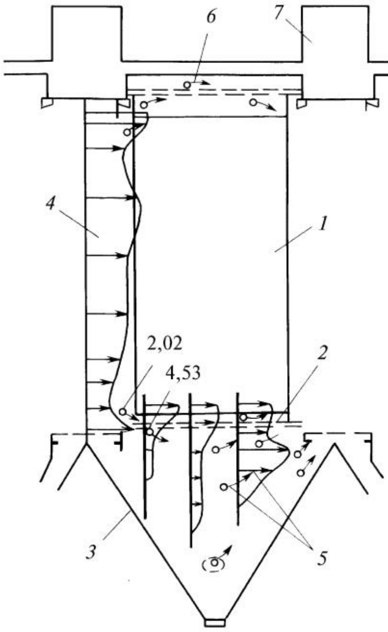
$$P = (1 - \varphi_p - \varphi_n)P_a + \beta\varphi_p P_a + \varphi_n \qquad (1.25)$$

where P_a is the ash slip without considering gas leakages through the semi-active and inactive zones; β – a factor, considering an increase in the ash slip degree in semi-active zones, β = 2…3; φ_p, φ_n — a part of flow passing through the semi-active and inactive zones. A part of the flow passing through the semi-active zones can be determined from the following expression:

$$\varphi_p = 1 - \frac{H_d}{H_{pr}} \quad (1.26)$$

where H_d and H_{pr} are the height of discharge and precipitation electrodes, accordingly.

To reduce gas leakages through the bottom inactive zone gas cutters at the ESP inlet and the walls inside the hoppers are applied. In MPEI studies at different options of installation of the walls inside the hoppers have been conducted, headed by prof. L.A. Richter. The research results presented in Fig. 1.29 *a*, *b*, show that vertical walls inside the hoppers are ineffective.



a)

Configuration of hopper walls	φ_n at a number of fields	
	3	4
	0,023	0,01
	0,022	0,009
	0,020	0,008
	0,002	0,001

б)

Fig. 1.29. Diagram of dust and gas flow through the inactive zones:
a — flow in the ESP field, where *1* - active zone, *2* - semi-active zone, *3* – hopper; *4* - velocity field in the active zone; *5* - velocity field and flow direction in the bottom (hopper) inactive zone, *6* - flow in the upper inactive zone, *7* - insulating boxes; *б* — flow through the ESP hopper, depending on the type and number of walls

In this regard, it was suggested to install the sloping walls inside the hoppers. As could be seen from Fig. 1.29 *b*, installation of three inclined walls results in about 10 times reduction of gas leakage through the bottom inactive zone in comparison with vertical walls. An angle of the walls is chosen to prevent ash deposition on the walls.

Ash collection efficiency depends on the mode of shaking of the electrodes. Time intervals between the shakings should be optimized for each field, as in each subsequent field an amount of the deposited ash decreases and, consequently, duration of shaking should be increased. Estimation of the optimal shaking mode, i.e. definition of a pause between blowing the same precipitation electrode in minutes, can be performed according to the following equation:

$$\tau = 16{,}7 \frac{A_p m_0}{V C_{in.p} \eta_p} \quad (1.27)$$

where A_p — field precipitation area, m^2; V — amount of gas entering the field, m^3/s; $C_{in.p}$ — dust content at the field inlet, g/m^3; η_p — efficiency ESP field cleaning, m_o — optimal dust capacity of the electrode, kg/m^2 (optimal dust amount per precipitation electrode surface unit before shaking).

Optimal dust capacity of the electrode is determined depending on the electrical resistivity of ash according to the empirical relation:

$$m_o = 3 - 0{,}25\lg\cdot\rho. \quad (1.28)$$

At a certain ash slip extent through the ESP, the ash slip through one field is determined by the ratio

$$P_p = P^{1/n}, \quad (1.29)$$

and the ash collecting efficiency by the ESP field

$$\eta_p = 1 - P_p = 1 - P^{1/n}, \quad (1.30)$$

where n is a number of fields along the gas flow.

Ash concentration at the inlet to the m-th field is determined by the expression

$$C_{in.p} = C_{in} P_p^{\,m-1}, \quad (1.31$$

where C_{in} — ash concentration at the inlet to the ESP first field.

In Table 1.12 optimum ratio of shaking intervals of precipitation electrodes, estimated by the described procedure, are presented. Ash collecting parameter at the uniform velocity field Π_p is determined from the empirical relationship:

$$\Pi_p = 0{,}2K_{fa}\sqrt{\frac{\upsilon}{u}}\frac{nL_f}{t} \quad (1.32)$$

where n is a number of ESP fields, L_f is a length of one field, m; t — distance between the precipitation and discharge electrodes; K_{fa} — factor, considering re-entrainment of the collected ash, determined according to the expression

$$K_{fa} = K_h K_{el} K_{sh}\left[1 - 0{,}25(u-1)\right], \quad (1.33)$$

where $K_h = 7{,}5/H$ — factor, considering that raise of the electrode height H results in re-entrainment increase because a part of ash does not have time to precipitate in the hopper; K_{sh} — factor, considering a mode of shaking. With occasional shaking under optimal conditions K_{sh} = 1,3 for the three-field ESPs, and for the four-field ESPs K_{sh} = 1,7; K_{el} — factor, considering the type of electrodes, for the modern electrodes with the fixed-point discharge K_{el} = 1.

Table 1.12. **The optimum ratio of precipitation electrode shaking intervals η**

Field number	ESP efficiency			
	0,95	0,98	0,99	0,999
Three-field electrostatic precipitator				
1	1	1	1	1
2	2,7	3,7	4,6	10
3	7,4	13,6	21,5	100
Four-field electrostatic precipitator				
1	1	1	1	1
2	2,1	2,7	3,2	5,6
3	4,5	7,1	10,0	31,6
4	9,6	18,8	31,6	178,0

The drift velocity is determined by the expression:

$$\upsilon = 0{,}25 E^2_{ef} d, \qquad (1.34)$$

where d — diameter of ash particles, m; E_{ef} — effective electric field intensity defined by the expression

$$E_{ef} = K_{о.к} E, \qquad (1.35)$$

where $K_{о.к}$ — factor, considering reduction of ash collecting efficiency in the presence of inverse crown (Table 1.13).

Table 1.13. **The average electric field intensity E and $K_{r.c}$ factors for fly ash of some types of power coal in Russia**

Coal rank	E, kV	$K_{r.c}$
Kuznetsky T	240	0,62
Ekibastuzsky SS	240	0,83
Podmoskovny B	245	1,0
Donetsky ASh, GSSh	250	1,0
Kansko-Achinsky B	280	1,0

In case of exact calculations of the drift velocity by the formula (1.35) each separate fraction of ash should be considered. To simplify the calculations ash sieving can be characterized by an average median diameter d_{50} (d_{50} - is a diameter of the sieve mesh, with 50% of ash by weight remaining on the sieve).

To simplify the calculation, formula (1.35) is written as

$$\vartheta = 0{,}25 E_{ef}^2 d_{50} \qquad (1.36)$$