

Monitoring of Electrostatic Fire and Explosion Hazards at the Inlet to Electrostatic Precipitators

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Abstract: The paper deals with the continuous monitoring of electrostatic fire and explosion hazards that can occur at the inlet to electrostatic precipitators (ESPs) when highly charged dust particles are transported by a gas carrier that can be the mixtures of both incombustible and combustible flue gases. The risk of ignition and even explosion is especially high in the presence of an explosive mixture of oxygen and, e.g., hydrocarbons, carbon monoxide, etc. To avoid the danger of electrostatic discharges and their consequences for a whole installation including an electrostatic precipitator a method and a specially designed and built system should effectively enable the continuous monitoring of the hazards and should immediately manage any automatic control system or some control elements. Some theoretical considerations concerning the method proposed, the physical quantities that must be measured, and the derivation of a novel dynamic safety criterion for assessing the risk of hazardous electrostatic discharges are presented. Finally, the author presents and discusses the possible practical application of the microprocessor-based measuring system verified experimentally in the past to the continuous monitoring of the hazards and to the management of an automatic control system to be put into operation.

1. Introduction

Still little is known about electrostatic fire and explosion hazards as a result of tribocharging and electrostatic discharges especially during the pneumatic transport of solid particles in pipelines and during filling silos, vessels, bins, etc. though explosions in the foodstuffs and petrochemical industries occur rather frequently [1]. The mechanisms of tribocharging and their contribution to the final stage of charging of any solid object in both the micro- and macroscopic scales are not well recognized since there is still a lack of a general theory of electrification of a matter under dynamic conditions. The processes of charging and discharging under such conditions are not too well known and understood because dusts, powders and other granular solid materials dispersed in a gas carrier in a pipeline generate the problems in their transport that are much more complex than those in the case of liquids [2]. This is so because the process of exchanging the charge between solid particles and pipe walls is complex and depends upon many various factors, e.g., the flow velocity, the angle of

impact, sliding, rolling, rubbing, and bouncing. The process also depends upon the shape, size and type of solid particle (an elastic or inelastic, or rigid body) that take part in elastic or inelastic collisions between the particles themselves as well as their impacts with a pipe's wall. This is also closely connected with the different intrinsic physical and chemical nature of both types of materials [3–7].

There are a lot of factors and parameters that characterize solid particles being pneumatically conveyed as well as the parameters of a transport installation and transport itself these having important influence on any nuisances, disturbances, and finally fire and explosion hazards in the whole pneumatic transport system including a pipeline, silos, vessels, collectors, driers, and other elements of the system. In the case of solid particles, their features and properties can be as follows: their chemistry, the size distribution, the specific surface area, the resistivity and permittivity, some critical concentration, humidity (water content = equilibrium moisture content), etc. [4–6, 8–10]. Their pneumatic transport is characterized by its following parameters: the mean velocity, the mass flow rate, the gas carrier flow

rate, the dimensions of a pneumatic transport pipe (its cross-section area and length), the dimensions of a silo, vessel, etc., the configuration and shape of pipes (bends, elbows, constrictions, and their number, that intensify turbulence and tribocharging), their material, and finally the temperature and humidity of a gas carrier [e.g. 6].

All the above-mentioned features, properties, and parameters exert influence on tribocharging of solid particles and also determine the minimum ignition energy (MIE) of particulate material conveyed in a pipe [11–15]. If the maximum effective energy of an electrostatic discharge is greater than the MIE of dust particles then ignition of the dust suspended in air or in the mixture of more different gases is possible [13, 16]. It is especially hazardous when an explosive mixture contains oxygen and, e.g., hydrocarbons, carbon monoxide, etc. Under favourable conditions, the flame so formed and not extinguished at once (or just in time) can result in a fire and even an explosion. This is also possible in the case of electrostatic precipitators (ESPs) [17, 18].

Because the ignition source does not have to come from within an electrostatic precipitator (ESP), therefore one must continually and accurately monitor the zones in a certain distance before an ESP's inlet to properly and quickly prevent the risk of a fire and explosion. This risk can occur both when dispersed solid particles themselves have quite a high net electric charge to produce an electric spark; it is possible when an electric field strength between the charge and, e.g., the earthed duct's or ESP's wall exceeds the breakdown strength of air the value of which under atmospheric conditions is about $3 \times 10^6 \text{ V}\cdot\text{m}^{-1}$. (The breakdown strengths of different solids are of one to two orders of magnitude greater than that of air.) The charge on solid particles travelling in a transporting duct can be or is a bipolar one [16] because of the heterogeneous nature of various natural materials and can separate to form a kind of capacitor within the powder column in a duct, and then there is also some risk of electrostatic discharge within the column. Both above situations can be the source of ignition of the dust itself or the dust–gas mixture. One can predict that if the material being processed or burnt in a boiler is heterogeneous, its final form or the flue gas is also of a heterogeneous nature.

The statistics show that only in Germany the

electrostatic-type discharges constituted almost 8.7% of total of the 426 dust explosions in the years 1965–1985 [19]. These discharges in 18.6% were the most common and dominating ignition sources in conveying systems. There are not too many news and publications on the fires and explosions caused by electrostatic discharges in the ESPs. Some information is provided by some authors in their papers and by companies that supply products and services to protect people and industrial installations from the danger of a fire and an explosion [25–30]. FIKE Corporation in their leaflet gives the following information [29]: “Explosion history. Loss history for the past ten years due to dust explosions from FM Global Data Sheet 7-76: Four in electrostatic precipitators for a loss of \$2,988,000.”

To avoid, reduce, or only minimize any potential risk of nuisances or disturbances in the ESP's operation or of electrostatic discharges resulting in fires, explosions, or both in a duct at the inlet to the ESP or in the ESP's interior the author proposes to continuously monitor the electrostatic hazards during the gas–solid flows in the ducts transporting dusts, powders, and other particulates from boilers and other industrial processes to the ESPs. The idea and method for continuous monitoring the hazards and protecting the ESPs against them are presented below.

2. Theoretical considerations

2.1. About the method

The method proposed is a non-intrusive electrostatic one and based on the phenomenon of electrostatic induction, and permits the continuous real-time measurements of the physical quantities being characteristic of pneumatic transport and the constant monitoring of technological processes where required [7, 20–24]. It is especially useful where the fire and explosion hazards from static electricity occur.

The method can be applied to measurements of the following physical quantities:

- the electric charge of single solid particles or droplets suspended in a gas (air) carrier in the ambient, open air or enclosed ducts or pipes as in pneumatic transport;
- the net electric charge or dynamic space charge density of solid particles or droplets in a gas (air) carrier in the ambient, open air or flow-

ing in the pipes of pneumatic transport;

- the mass flow rate, volume loading, or concentration of charged solid particles in the pipelines;
- the mean flow velocity of charged solid particles in the pipelines.

It also enables one to compare measurement data with criteria values given in some dynamic safety criteria established by the author [25, 26].

In the method electrostatic flow probes are employed that are metal and of a ring shape. (By the way, the shape can be arbitrary.) These are mounted in a specially designed and built measuring chambers (heads) that are put in a duct, e.g. between two flanges. The probes have their sensing (viewing) zones where the probes are able to detect the net or any charge within the zones, which are always somewhat longer than the axial width of the single probe. The probe has such an area where the single charged particle travelling through it starts and ends to visibly induce charge and potential on the probe by electrostatic induction [e.g. 7].

The flow of charged particles in the duct or pipe generates electrostatic noise, which is a good source of information about the gas–solid flow parameters: the mass or volume flow rate, concentration or volume loading, mean flow velocity and about the particles' net charge. All the above mentioned quantities are measured indirectly through the measurement of the potential induced in the probe or of the voltage established between the probe and any nearby earth, e.g. the earthed housing of a measuring chamber in the interior of which the probe is located.

The description of the non-intrusive electrostatic method and the microprocessor-based measuring system based on it will be presented further in the text.

2.2. Some theory of measurements

To properly assess the electrostatic fire and explosion hazards in the ducts and pipes it is necessary to measure or know the net charge, as carried by dust, powder or another particulate solid both in flue gases or other gases, that flows to the ESP. The crucial parameters of the flow itself to be determined are the mass flow rate or volume loading and the mean flow velocity of solid particles.

In the further considerations instead of the ring probe, simply the probe is used because of different shapes of the cross section of a duct or pipe. The shapes can be circular, rectangular, or any other.

The mass flow rate $\dot{m}(t)$ for the constant specific density ρ of a disperse phase (solid particles), the cross-sectional area A of the transporting duct or pipe, and the mean flow velocity v is a function of the solids volume loading $\sigma(t)$

$$\dot{m}(t) = \rho A v \sigma(t). \quad (1)$$

The volume loading $\sigma(t)$ is linearly dependent on the net charge $q(t)$ of particulates being at any moment within the sensing zone [25] and is

$$\sigma(t) = \frac{q(t)}{q_{vs} V}, \quad (2)$$

where q_{vs} is the static space charge density and V is the sensing zone's volume.

It is assumed that in the volume V the velocity v of solid particles does not change significantly along the zone's length L at all. In addition, the distribution of particle velocity (the velocity profile) over the duct's (pipe's) cross section is uniform for fully developed turbulent flows.

From Eq. (2), it results that

$$q_{vd}(t) = q_{vs} \sigma(t) = \frac{q(t)}{V}, \quad (3)$$

where $q_{vd}(t)$ is the dynamic space charge density – the author introduced this term into the literature of the subject for the first time yet in 1990 [25]. The volume of transporting gas (air) V_o in the sensing zone is usually much greater than the volume of a disperse phase V_p and it can be assumed that the gas carrier's and sensing zone's volumes are equal to each other: $V_o = V$. The static space charge density is also constant in the sensing zone, as assumed.

With the use of the non-intrusive electrostatic method proposed one can measure the voltage $U(t)$ established between the probe and the earth – here an earthed housing of the measuring chamber (head). The net charge being within the zone induces potential $\phi(t)$ in the metal probe and as the voltage $U(t)$ can be measured by any measuring system built on the basis of the non-intrusive electrostatic method [7, 23, 24]. The known voltage measured simply permits the determination of the net charge $q(t)$ or dynamic space charge density $q_{vd}(t)$ af-

ter a measuring system has been calibrated. Hence, the determination of the mass flow rate $\dot{m}(t)$ and the volume loading $\alpha(t)$ [according to Eq. (1)] is also possible since [7, 31]

$$U(t) = \alpha q(t) = \beta q_{vd}(t) \quad (4)$$

and

$$\dot{m}(t) = \gamma q(t) = \delta q_{vd}(t) \quad (5)$$

where: α , β , γ and δ are the factors of proportionality, and $U(t)$ is the voltage measured between the metal electrostatic flow probe and the earthed measuring head.

The comparison of Eqs. (1), (4), and (5) shows that the voltage is also proportional to the mass flow rate and volume loading. Hence, the measurement of the voltage permits the simultaneous determination of both quantities.

The measurement of the mean flow velocity v of a dispersed phase in the duct is performed using two same probes separated by a distance L_{opt} in the chamber. (The distance L_{opt} is called an optimum, correlated one [7, 22, 31].) This distance can be determined experimentally, predetermined theoretically, or both.

The cross-correlation method is here employed to determine the transit time τ that is a measure of the mean flow velocity v according to the formula

$$v = \frac{L_{opt}}{\tau}, \quad (6)$$

where the transit time τ is obtained from the maximum of the cross-correlation function $R_{xy}(\tau)$ when two voltage signals $x(t)$ and $y(t)$ of both probes are convoluted (cross-correlated) by software [7, 22, 31, 32]. The cross-correlation function has a well-known form

$$\begin{aligned} R_{xy}(\tau) &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t - \tau) y(t) dt \\ &= \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t) y(t + \tau) dt. \end{aligned} \quad (7)$$

2.3. Dynamic safety criterion

The assessment of the electrostatic hazards is based upon the so-called dynamic safety criteria proposed by the author in 1990 [25, 26]. Those criteria were established for circular

transporting pipes of a given diameter D . As a result, the powder column of charged solid particles of a diameter D was also analysed.

Here the assumption is taken that solid particles travel downstream the duct of a rectangular shape. The flow is also a fully developed turbulent one and the cross section of a particles column is that of the dust.

The modified dynamic safety criterion for the electrostatic hazard's assessment in a rectangular dust is derived now. Let the duct has the width W and the height H within the sensing zone of the length L . The axial probe's width is w and $w < W$. The dimensions of the flow probe and its sensing

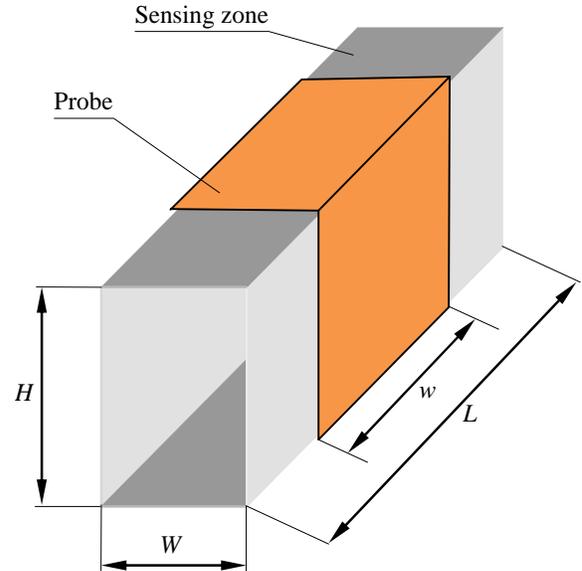


Fig. 1. The shape and dimensions of the flow probe and its sensing zone.

zone are shown in Fig. 1.

The *Gauss* law for the net charge within the zone is as follows taking also Eq. (3) into account

$$\oint_S E_d(t) dS = \frac{q(t)}{\epsilon \epsilon_0} = \frac{q_{vd}(t) V}{\epsilon \epsilon_0}, \quad (8)$$

where: $E_d(t)$ is the electric field strength on the side surface S of the powder column within the zone and is approximately equal all over the surface, as assumed, and $S = 2(W + H)L$; $V = WHL$ is the zone's volume; ϵ is the relative permittivity (dielectric constant), and ϵ_0 is the

permittivity of free space ($= 8.854 \times 10^{-12} \text{ F} \cdot \text{m}^{-1}$). The electric field strength is then

$$E_d(t) = \frac{q(t)}{2\epsilon\epsilon_0(W+H)L} = \frac{q_{vd}(t)}{2\epsilon\epsilon_0} \frac{WH}{W+H}. \quad (9)$$

To get the dynamic safety criterion the electric field strength from Eq. (9) is compared with an upper limit of the electric field strength E_m (the breakdown strength of air) whose value is $E_m \cong 3 \times 10^6 \text{ V} \cdot \text{m}^{-1}$ in the ambient air under uniform electric field conditions and normal temperature and pressure. The condition $E_d(t) < E_m$ must then be satisfied and the following relationship is obtained

$$\frac{q(t)}{2\epsilon\epsilon_0(W+H)L} = \frac{q_{vd}(t)}{2\epsilon\epsilon_0} \frac{WH}{W+H} < 3 \times 10^6 \text{ V} \cdot \text{m}^{-1}. \quad (10)$$

Multiplying both sides by $2\epsilon\epsilon_0$ and taking $\epsilon = 1$ (for air) into account gives the following dynamic safety criterion

$$\frac{q(t)}{(W+H)L} = \frac{WH}{W+H} q_{vd}(t) < 5.3 \times 10^{-5} \text{ C} \cdot \text{m}^{-2}. \quad (11)$$

As said above, the measurement of the voltage $U(t)$ gives information about the net charge $q(t)$ or its dynamic space density $q_{vd}(t)$ and for the known and constant sensing zone's dimensions W , H , and L , a specially designed, built, and programmed microcomputer-based system can monitor continuously the time-variations of the net charge or its space density and compare with the right side of the inequality in Eq. (11). The criterion in Eq. (11) can, of course, be rearranged and instead of $q(t)$ or $q_{vd}(t)$, one can apply, e.g., $U(t)$. The dynamic space charge density is proportional to the volume loading and simultaneously to the mass flow rate and mean flow velocity. Hence, it is necessary to monitor the variations of these mechanical quantities that characterise the gas–solid flow in the duct and which affect the process and level of tribocharging, which in turn can result in an electrostatic hazard.

3. Practical application

The non-intrusive electrostatic method is based on the phenomenon of electrostatic induction and permits the continuous real-time measurements

of all the quantities described above and apply the dynamic safety criterion established – Eq. (11). On the basis of the method the microprocessor-based measuring system was built to enable the constant, routine monitoring of different technological processes where required [7, 20–24]. Thanks to a special software program the system can measure the basic, required quantities, and can calculate end numerical values according to the left side of the dynamic criterion, as in Eq. (11), for given (here: W , H , and L) and measured [e.g. $q(t)$ or $q_{vd}(t)$, or $U(t)$] values. Finally, when the criteria, permitted, and safe levels, as results from the comparison of the left side with the right side of the inequality in Eq. (11), are reached or exceeded, then the system can apply accepted standard procedures immediately to decrease the flow velocity, to reduce the mass flow rate, to partly (or even entirely) neutralize the charge, etc. To use the procedures a special executive system must be added that is coupled with the microprocessor-based system to manage the operation of a control element (or elements), an actuator (actuators), etc., or to activate process control equipment or an automatic controller (controllers), or to manage a whole automatic control system, if necessary.

The whole system for monitoring the electrostatic hazards is shown in Fig. 2 in a simplified form, as is a fragment of the pneumatic transport installation as the one to be used to convey dust-laden gas to the ESP. The fragment consists of the following parts: an earthed housing of the measuring head (1) which is an electromagnetic screen to protect the interior of the chamber against any spurious external interferences and provides a mechanical support; two metal electrostatic flow probes (2); flanges (3) to enable one to insert the chamber into the duct; an earthed duct (4) along which the dust-laden gas is conveyed downstream to the ESP; a dielectric fragment of a duct (5) on which the flow probes are mounted, and an electrostatic precipitator (6).

Two stochastic, analogue signals $x(t)$ and $y(t)$ of both probes are the voltage signals. These are proportional to electrostatic noise generated by the flow of charged particles within the sensing zones of both probes. The noise induces potential and charge in the probes by electrostatic induction. The probes are very sensitive sensors and can detect even the smallest fluctuations in the noise. Each of the signals is initially amplified by

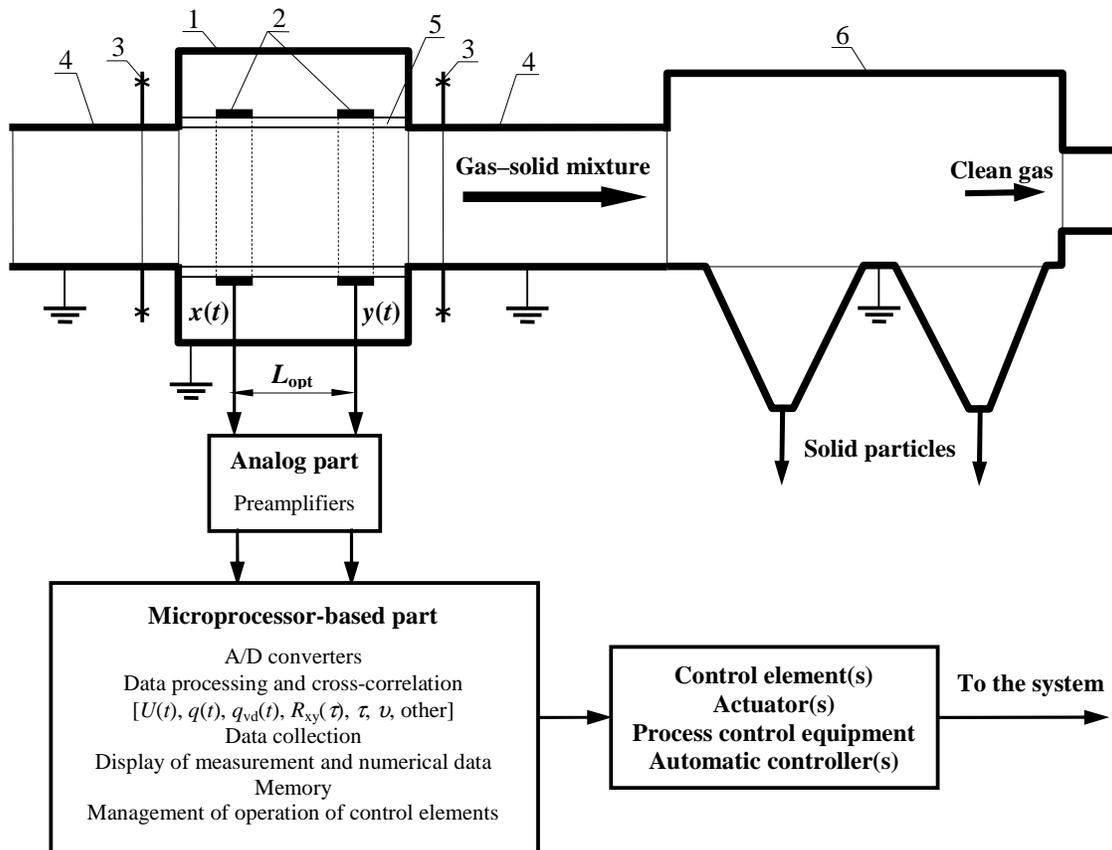


Fig. 2. Schematic of a fragment of the pneumatic transport installation for conveying a dust-laden gas to an electrostatic precipitator and the system for monitoring the fire and explosion hazards. Description in the text.

preamplifiers to be converted by analogue-to-digital (A/D) converters with the relatively small error of quantisation that is to use their full dynamics [32]. The preamplifiers should be located as close as possible to the probes and therefore they are inside the head. The A/D converters are also put in the head.

Before any measurements and use in a given installation the microprocessor-based system has to be calibrated. The voltage measured is proportional to the net charge as is the mass flow rate or volume loading – Eqs. (4) and (5). The charge is dependent on the humidity of air, and especially on the equivalent moisture content of solid particles. Therefore it is crucial that the system's calibration be performed for a given range of the equivalent moisture contents. It is obvious that such calibration “takes account” of other conditions existing in a given duct or installation including its geometry and dimensions, and the intensity of two-phase gas–solid flow and the dominating, principal type of solids flow pattern – homogeneous, stratified, annular, roping, etc.

There is no need to calibrate the system when it works only as the one for measuring the mean flow velocity with the use of the cross-correlation method which is not sensitive to any spurious signals that are strongly rejected since they have no correlation with the input signals. The system then determines only the transit time of a tagging signal (a frozen flow pattern) in the flow of solid particles that travel downstream between two electrostatic flow probes separated by L_{opt} .

The digitised measurement data are processed to obtain information about the net charge, dynamic space charge density, mass flow rate, volume loading, and so forth. These values can be obtained from only one probe. The microprocessor-based measuring system displays all the data obtained and collected from both measurements and calculations, and next the data are stored in a system's memory.

When the value calculated of the left side of the dynamic safety criterion tends to, reaches or exceeds the right side value, then the microprocessor-based measuring system starts immediately

to manage the whole automatic control system or only some control elements. For instance, it can cause the flow velocity of dust-laden gases to be reduced, a charge neutralizer to be turned on, and/or an inert gas to be let into a duct, and so on. Sometimes one must take other necessary and effective safety or precautionary measures. All the safety measures must be used appropriately, precisely, and according to the safety guidelines and technological requirements.

4. Concluding remarks

It is believed that presented and proposed here the way of monitoring and protecting these installations at the end of which the ESPs are located seems to be effective and useful under real industrial conditions. The non-intrusive electrostatic method and the microprocessor-based measuring system were worked out many years ago and verified experimentally in long-lasting laboratory tests and in a technological installation. The results of those experiments were published extensively over around 15 years and were used by many authors in their work. Therefore it is possible and even necessary to try to employ the method and especially the microprocessor-based system in a real installation at the inlet to the ESP. It is advisable that the routine monitoring be carried out where really explosive dust-laden gases occur and the electrostatic fire and explosion hazards are potentially high.

It is worth mentioning that in some cases in the dynamic safety criterion one can apply, e.g., the 10% factor of safety. It means that the right side value in Eq. (11) can be lower by 10%.

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