Some Experiences in the Exploitatation of Triboelectric Sensors for Measuring Concentration of Particulate Matter on Thermal Power Plants

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Abstract **— Environmental pollution problems are the outcome of the worldwide increase in energy consumption and industrial growth. The overall concentrations of waste gasses, including the particulate matter emission has increased. The fine 1–100 μm, particles particularly harmful and being a well-known health risk. Large industrial plants (cement plants, thermal power plants, etc...) require dust cleaning equipment, advanced particulate monitoring, measuring of their emissions and on-line pollution control. Control goals include the need to meet the environmental regulations, keeping at the same time the power losses and the overall energy consumption under control, in order to reach the energy efficiency goals. These regulations impose very stringent levels for upper concentration limits 50mg/m^3 of emitted particulate matter. The tendency is to reduce these levels to the values less than 20mg/m^3. A very important factor in satisfying these requirements is a reliable and accurate particulate monitoring and measurement. One possible way of measuring the concentration of particles is to use triboelectric effect. The principle of triboelectric dust measurement is that whenever a dust particle hits an electrically loaded metal stick, which has been placed across a flue gas duct, the charge of the metal stick is changed. The more dust particles hitting the stick per time unit, the more it influences the metal stick. The changes in the charging of the metal stick are an expression of the dust concentration of the process. In this article are presented some experiences and experimental results in the four years exploitation of triboelectric sensors for measuring and monitoring concentration of particulate matter in electrostatic precipitator (ESP) station on thermal power plant (TPP) "Morava"-Svilajnac.**

Key words-Air pollution; dust particle; particle concentration; triboelectric effect; thermal power plants

I. INTRODUCTION

The largest sources of particulate matter emission in the atmosphere are large boiler furnaces of thermal power plants, thermal station as well as cement and metallurgy plants. During combustion of fossil fuels, along with oxides of combustible elements (carbon, hydrogen and sulphur), are emitted into the atmosphere particulate ash, unburned coal, nitrogen oxides and other pollutants in small quantities. The ash emissions during combustion of solid fuels depend on the mineral part of the fuel, combustion method, type and efficiency furnace dedusting.

A particle from the air mechanically and chemically acts on the life flora and objects. Mechanical effect is reflected in the deposition of particles in some parts of the plants and objects, which under the influence of moisture cure forming solid crust that slow down plant growth. The chemical particle effect is manifested by absorption of active gases such as SO_2, NO_x, CO, etc. They are due to moisture in the air creates aggressive compounds that destroy the surface on which drop. These gases caused by moisture in the air create aggressive compounds that destroy the surface on which drop. It is especially large impact particles that come from the air to human respiratory system. The particles enter in the human body to the respiratory system, still in the blood and other tissues where they accumulate. The coal is burned in combustion boilers in scattered form, and therefore, as a product of combustion gets very large amount of fly ash. To prevent the waste ash particles from the chimney on the environment is applied special ecological equipment. The principal block scheme, having this equipment is shown in Fig.1.

Contemporary dust cleaning equipment comprises electrostatic precipitators (ESP), forcing the waste gas to flow between large electrode plates, exposed to DC voltages of several tens of kV. Exposure to high strength electric field charges dust particles and they migrate towards the collecting plate, which is the positive one, and in most cases grounded. The other, negative electrode is attached to the negative supply rail of the controllable DC voltage source. The electrode surface is barbed and equipped with appropriate protruding spikes, responsible for an enhanced ionization. The migration of the charged dust particles takes place due to the electric forces exerted by the field. The drift velocity of the particles and their collection efficiency largely depend on the gas speed and the eventual turbulent flow [1].

To enhance the precipitation function, the ESP comprises several series connected sections (input, middle and output), wherein the output gas from the previous section becomes the input to the next.

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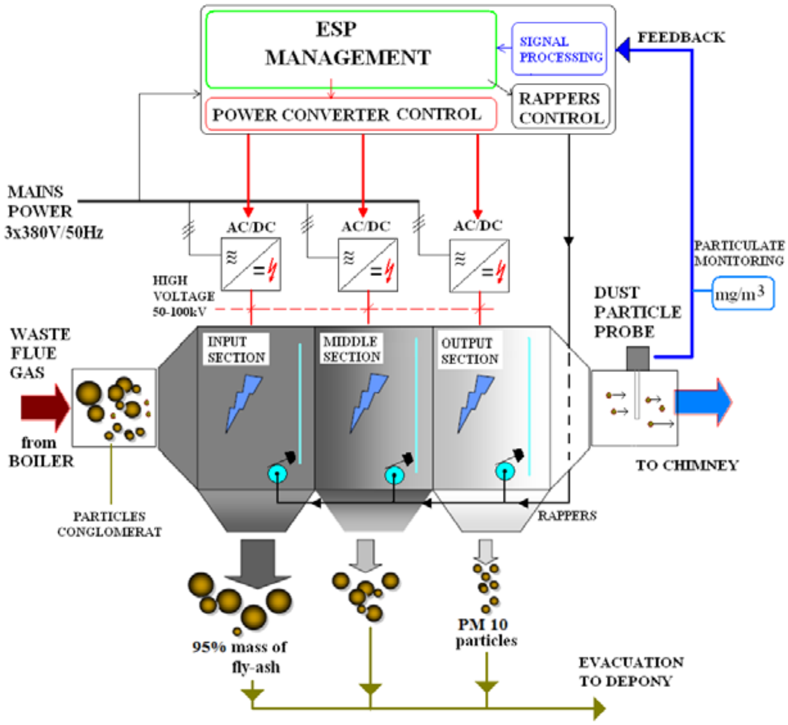

Figure 1. Typical disposition of ESP plant having particulate matter pollution control.

In such cases, the subsequent section may collect the dust particles that were properly ionized within the previous section, but were not collected due to an insufficient particle drift and/or too large speed of the gas stream.

The input section of the ESP collects major part of the waste flue gas (particle conglomerate). Collected particles are mostly of a larger diameter. Roughly speaking, the input section collects the particles with D > 10-50μm, accounting for more than 90% of the overall weight. Flue gas exiting the input zones caries small particles to middle section. Majority of particles collected in the middle and the output zones are small particles, with the diameter D < 10μm. When collected into the dust layer, residing on the collection plates, these small particles result in elevated resistance, which may exceed the resistance of the input-zone dust by an order of magnitude. The root cause for this is plane fact that most of the resistance, encountered by the *electric wind* current, passing through the dust, comes from the need for the charges to pass from one particle to another [2].

In standard ESP management systems are include integration of voltage control, rapping collecting and emission electrodes, and adaptive intermittent power for improved overall collection efficiency [3]. Time-based and spectral analysis of voltages and currents helps the estimation of the dust layer thickness and resistivity, relevant for the voltage and rapping control. Adaptive rapping with simultaneous voltage profiling helps clean the electrodes and reduces particles re-entrance.

A very important element in the best performance ESP management is on-line pollution control. These require advanced particulate monitoring and measuring of pollutants emission. Also, control goals include the need to meet the environmental regulations, keeping at the same time the power losses and the overall energy consumption under control, in order to reach the energy efficiency goals. These regulations impose very stringent levels for upper concentration limits 50mg/m^3 of emitted particulate matter. The tendency is to reduce these levels to the values less than 20mg/m^3. A very important factor in satisfying these requirements is a reliable and accurate particulate monitoring and measurement.

One possible way of reliable measuring the concentration of particles is to use DC or AC coupled triboelectric effects. These effects can be described in the next section.

II. Triboelectric Effect

The small particles of fly ash suspended in a flue gas stream will carry an element of electrical charge that is generated from friction with other particles and metal surfaces. This phenomenon is referred to as the triboelectric effect. The charge carried is proportional to the surface area of the particle, and for particles of a given size, to the mass of the particle.

If a conducting probe is inserted into the gas stream, particles in the stream will collide with the probe and charge will be transferred to the probe as a result of the collisions. If a conducting probe is inserted into the gas stream show in Fig.2, particles in the stream will collide with the probe and charge will be transferred to the probe as a result of the collisions. A triboelectric particulate monitoring device (conducting probe and transmitter) measures the direct current I_μ produced by the charge transfer when particles strike the probe.

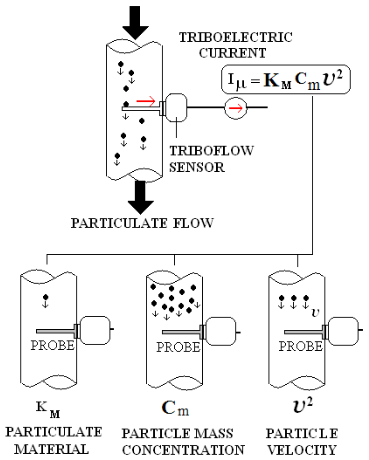

Figure 2. Triboelectric effect and the factors which affect on the output current signal.

In really industrial conditions triboelectric signal is made up of several components [4]:

- DC component generated by the particulate striking the sensor. It is proportional to the mass flow and varies with the actual flow rate.
- The low frequency AC component generated by short-term intermittent variations of fluctuations in the mass flow rate of particulate, and by particulate passing near the probe, but not impacting the probe.
- The high-frequency AC component. This is the high-frequency modulation resulting from equipment, vibration and other factors.

The high-frequency AC component is unusual and must be filtered. Only the DC component and the low-frequency AC component are useful. Early in the development of triboelectric devices, engineers recognized the advantages of the DC measurement in providing robust and linear signals. They also found that at low velocities and concentrations, the DC component becomes smaller than the AC component of the signal. For this reason, some triboelectric technology incorporates a special circuit that automatically reports the larger of the two components.

The technologies utilizing subsets of traditional measurement methods: non-contact electrification [4]-[5] and electro dynamic measurement [6], also filter out the high-frequency AC component, but they rely completely on the low-frequency AC component for a signal.

The triboelectric phenomenon is very complex and is a function of several mechanisms which are investigated and described in detail in literature [7]-[12]. The factors that contribute to charge transfer between contacting materials include type of particulate material, velocity and surface roughness, adsorbed gases (like moisture), particle concentration and size, pre-existing charge, etc.

In first approximation, the current signal I_μ (see Fig.2), which arises from the charge transferred to the probe by particulate impinging on the probe surface, is a function of several factors as indicated in the equation [4]:

$$I_\mu \approx K_M \cdot C_m \cdot v^2 \qquad (1)$$

where are:

I_μ - Triboelectric signal i.e. current, in [A]

C_m - Mass concentration of the particulate impinging on the conducting probe, in [mg/m^3]

v - Velocity of the gas stream, in [m/s]

K_M - The calibration factor that consider the type of particulate material, in [A·m/s^2·mg]

Each material exhibits a different K_M factor. The signal also increases with velocity by a square root relationship, whether using DC or AC components. The material and velocity are fairly constant in most ESP application, with the result that the signal follows the changes in the mass concentration, except when only the AC component is used. AC-coupled circuits utilizing only the AC components are completely dependent on fluctuations in the dust flow signal to function. If fluctuation or turbulence does not exist in the case of laminar flow, the dust will not be detected [5].

If the degree of fluctuation varies to any extent, the dust flow will be detected as significantly lower or higher amounts than actually are present. Significant changes take a long time to settle down. These can be interpreted as changes in particulate concentration because there is no way to know the difference.

The AC coupled triboelectric measured principle by an electrically isolated sensor probe which is connected to processing electronics, is shown in Fig.3.

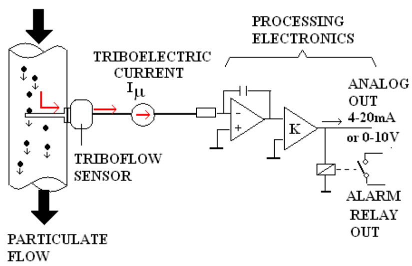

Figure 3. Triboelectric measuring having processing electronics and relay alarm.

Multiple particle strikes create a small flow of current I_μ through the instrument. The current I_μ is proportional to the momentum (mass times velocity squared) of the particles. The resulting current is amplified, filtered, rectified and further filtered looking only at the AC component, giving a linear representation of the concentration or mass flow rate of the particles in the gas stream. Amplification electronics convert the current to an instrument output signal (voltage 0-10V or current 4-20mA).

The reason for measuring the AC component is that, compared to the DC component, the electronics are more sensitive. The AC signal is substantially less affected by influences such as amplifier noise and process parameters, which includes the build-up of process dust on the sensing rod.

In addition to analogue outputs, as part of the measuring device is usually provided one digital relay output which gives the status of the alarm is reached, or the maximum concentration of particles in the flue gas stream.

III. Application and Testing Triboelectric Sensors on TPP "Morava"

Since June 13th 2008 until July 21st 2010, the testing took place at TPP "Morava"-Svilajnac, equipped with conventional SCR-50Hz (4 pieces) and high voltage high frequency (HVHF) ESP power supply units (4 pieces). The measurements were organized in order to the comparison HVHF power units with conventional SCR units; examine the effects of HVHF power supply on the precipitation efficiency and to establish the expected reduction in dust emission. In addition to these tests are obtained and some experience in the use of AC coupled triboelectric sensors type EM5, Tyco-GOYEN production. All technical data, performances and user manuals for these sensors are provided in the manufacturer's documentation that is available in the references [13]-[14].

Otherwise, before installation this measurement system in recirculation channel on TPP "Morava", not exist any system for on-line monitoring the concentration of particles in the flue gas. Until then they only made periodically measurements (every 6 months), with a mobile measuring station, of flue gas emissions at the entry of output chimney. In these measurements were also included the auxiliary measurement in flue gas: temperature, pressure, concentration O_2, velocity ...etc, and then the application procedures for the gravimetric determination of particle concentration in the flue gas.

The following equipment was installed at the ESP plant on TPP "Morava":

- Four high voltage high frequency power sources for the ESP
- HV splitter with selector switches which enables the ESP supply either from conventional 50 Hz T/R units or from the high frequency power sources
- The P/Q/S/Energy measurement group for logging of the active, reactive, apparent, and distortion power, as well as active and reactive energy;
- AC coupled triboelectric dust particulate emission monitor (sensor head plus measuring electronics) type EMP5 *Tyco*-GOYEN production, mounted in the recirculation pipe channels of ESP plant.

Fig.4 shows the block diagram with the specified equipment mounted in TPP "Morava". The HV splitter system enables hot-swap selecting either the conventional T/R units or the HF power supplies in the course of the ESP operation. Hence, comparison of the two was possible in almost identical conditions. In this way it is possible to determine the best solution with regard to precipitation efficiency.

The triboelectric sensor probe (steel road with sensing head) is mounted in the recirculation pipe of the right ESP branch. This mounting location has been selected so that the gas flow is laminar so as to insure stability and accuracy. Only in this mounting location is possible to meet the requirement 3D (D is diameter of recirculation pipe, and it is equal to 1.5m), in order to avoid the effects of pipe curvature and the effects of turbulence (see Fig.4). Alternative solutions, i.e. eventual mounting within the post-confusor channel has been abandoned, since it was not possible to identify location that would be far enough from the channel curves or the fan, so as to ensure a laminar flow. As it is well known, mounting of the triboelectric probe in zones with pronounced turbulence contributes to significant errors.

The data acquisition system consisted of *RISCH Multi 18S* analogue-digital multimeter of high resolution, with serial RS 232 port, digital oscilloscope, plotter, and industrial PC system. The multimeter features auto-ranging for all measuring ranges. Auto-ranging is automatically selected after switching the meter on. According to the measured quantity applied, the meter automatically selects the measuring range which gives the best resolution. The multimeter is connected via a serial connection RS 232 to the PC module. In the PC module are fully performing to all calculations of actual concentration of particles, as well as the necessary calibrations. The output from this block gives the concentration in [mg/m^3], reduced to reference conditions (pressure 1013 mbar, temperature 0°C and oxygen content of 6%). Therefore, in order of calibration was required to install in the recirculation pipe channel precision measuring station, in which real values are obtained (oxygen concentration [%], pressure [mbar], humidity [%], temperature [°C], velocity of gas stream [m/s]) and used in calculating the actual concentration of pollutants in flue gas (including the concentration of particles). Also, as an input data is given type of coal and the ash and sulphur content in it.

In the exploitation testing and examination is used the formula (in accordance with the legislative regulations) for calculate corrected concentrations C_c of particulate matter compared to normal condition (temperature 0°C, pressure 1013mbar, dry gas and concentration of reference oxygen 6%):

$$C_c[mg/m^3] = C_m[mg/m^3]\cdot\frac{21-O_{2REF}[\%]}{21-O_{2M}[\%]}\cdot \\ \cdot\frac{1013.25}{p_{bar}[mbar]}\cdot\frac{100}{100-W[\%]}\cdot\frac{T}{273.15[K]} \qquad (2)$$

Where they are:

C_m - measured particle mass concentration [mg/m^3]

O_{2M} -measured concentration of oxygen [%]

O_{2REF} -reference value of oxygen concentration (for coal combustion 6%) [%]

p_{bar} -barometric pressure [$mbar$]

W -moisture content in the flue gas [%]

T -absolute temperature of flue gas, $T[K]=t[^0C]+273K$

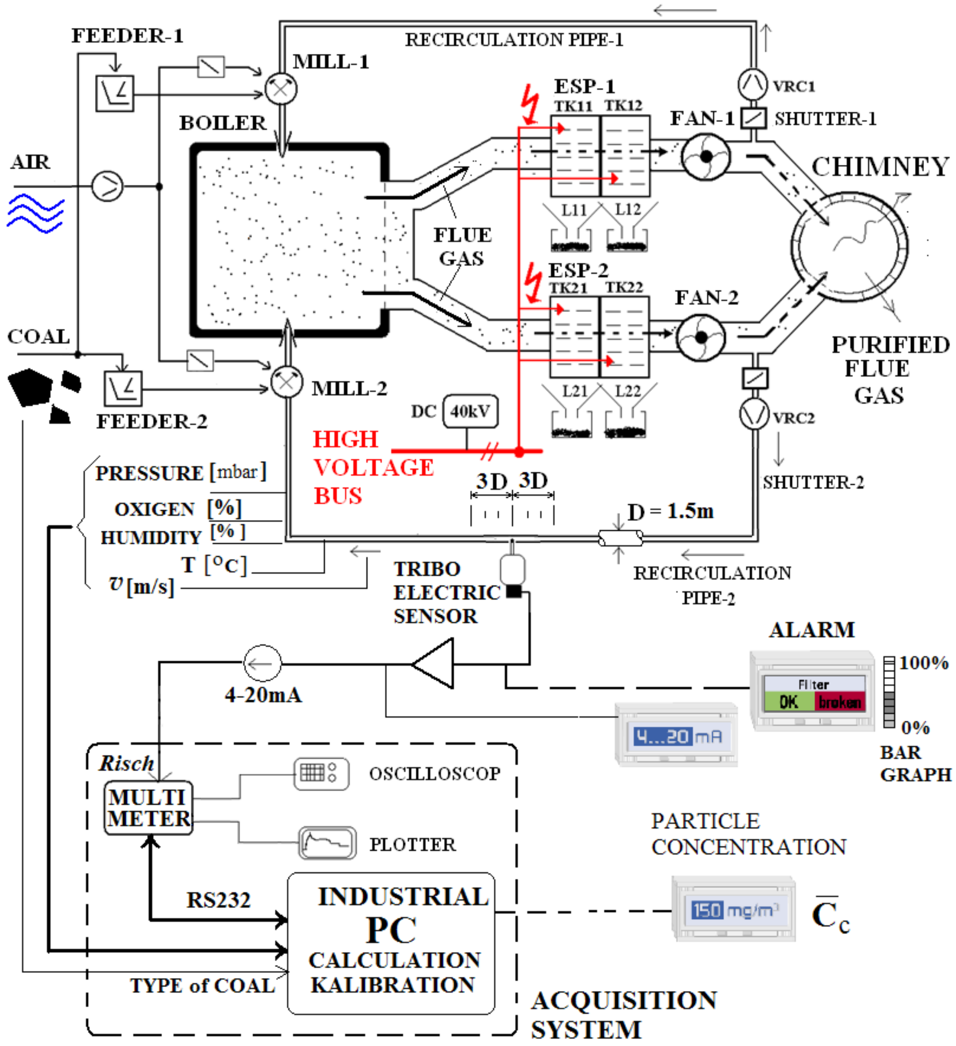

Figure 4. Block diagram of measuring equipment in ESP plant on TPP "Morava".

IV. Experimental and Measuring Results on TPP "Morava"

In this chapter will be presented a part of experimental results concerning of particulate matter concentration measurements obtained by the exploitation investigations in the ESP plant at TPP "Morava". All measurements were achieved in the recirculation channel, since there is only possible to fulfil the requirements installing the triboelectric sensor for measuring the concentration, with the avoidance of turbulence. In other words, in this way can be said to have laminar flow of flue gases and particles within it.

The experimental results presented below were obtained at power of the TPP block 105.6MW and the following operating conditions of ESP plant: temperature of flue gas $T = 175^0C$, moisture content of flue gas $W = 23\%$, ash content in coal 22%, sulphure content in coal 0.52%, barometric pressure $p = 996mbar$ and oxygen concentration in flue gas $O_{2M} = 8.56\%$.

Fig. 5 shows the record of the measured current values of the particle mass concentration in the recirculation channel of right branch ESP plant, in which they were, connected two HVHF power supply unit for electrostatic precipitation. On the vertical axis is shown current value of the particle concentration in the recirculation channel expressed in [mg/m^3], while the horizontal axis shows the time interval during which the measurement was performed. Average value the particle mass concentration was $\hat{C}_m = 44.5mg/m^3$. Calculation in relation to the operating conditions, according to the relation [2], it was obtain that the corrected value of the concentration is $C_C = 2.61 \cdot \hat{C}_m = 116mg/m^3$.

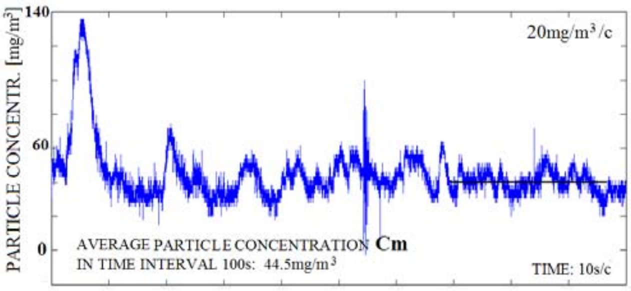

Figure5. Measuring particle concentration in recirculation pipe channel at 2xHVHF power.

This record shows, that at the beginning of the interval of 100s, the value of the particle mass concentration is significantly above the measured average values and that its value is about $\hat{C}_m = 140 mg/m^3$. This is the result of rapping collecting electrodes in right branch of ESP plant. Not showing the whole interval rapping which lasts about 2min, but only the end of rapping, which is sampled the last peak in particle mass concentration.

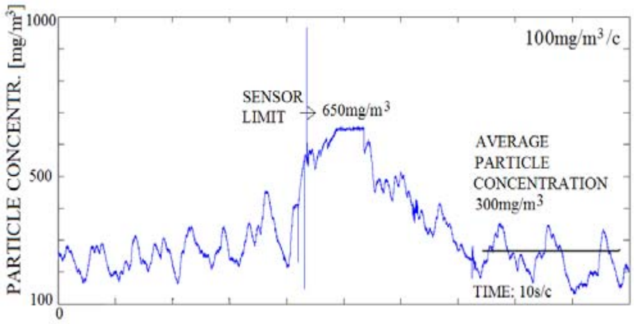

Figure 6. Measuring particle concentration in recirculation pipe channel at transient regime of power changing: 2xHVHF power to 2xSCR-50Hz power.

Fig. 6 shows the transient regime, which refers to the power supply change in observed branch of ESP installation. HVHF power was changed with SCR-50Hz power. During the reporting time interval, can be observed three characteristic intervals. In the first time interval, which lasted about 1min, there was an increase current particle mass concentration from 200mg/m³ to about 500mg/m³, and then in the second interval (which lasted about 20 seconds to reach the limit of the measuring sensor), to the value of 650mg/m³. In the third time interval, there was a reduction in the value of the particle mass concentration to 300mg/m³. It is observed the relatively large fluctuations in the particle concentration in first interval, especially in the third interval. In the second interval, when both power supplies are turned off, the signal of concentration reaches the limit and the fluctuations become negligible.

Fig.7 shows the actual measured value of the particle mass concentration in the recirculation pipe channel in the right branch of ESP plant, in which they are, connected the two SCR-50Hz power supply units. Average value the particle mass concentration in this time interval was $\hat{C}_m = 180 mg/m^3$.

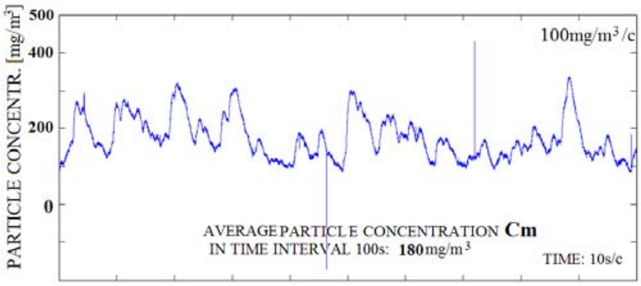

Figure 7. Measuring particle concentration in recirculation pipe channel at 2xSCR-50Hz power.

Calculation in relation to the operating conditions, according to the relation (2), it was obtain that the corrected value of the concentration is $C_C = 2.61 \cdot \hat{C}_m = 470 mg/m^3$. It is observed the intensive fluctuations of particle mass concentration signal, so that the peak value was approximately 300mg/m³.

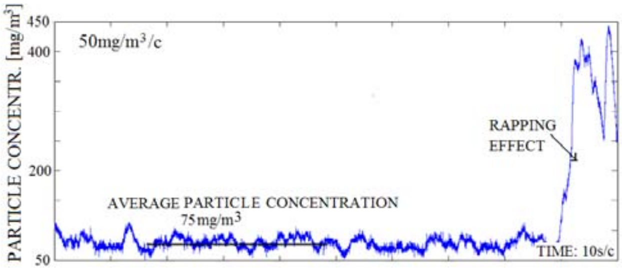

Figure 8. Measuring particle concentration in recirculation pipe channel at transient regime of turning on rapping mechanisms; 2xHVHF power.

In Fig. 8 is given the record of the current value of the particle mass concentration at switching on of electrode (collecting and emission) rapping mechanism.

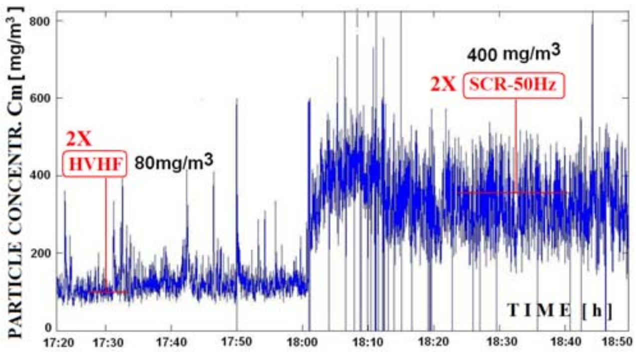

Figure 9. Comparison of particle concentration in recirculation pipe channel for 2xHVHF power and 2xSCR-50Hz power.

In that time interval there has been a significant increase in of the particle mass concentration of 75mg/m³, up to the value of about 400mg/m³.

Fig.9 shows a comparison of the effects of flue gas cleaning for the use of HVHF and conventional SCR-50Hz power supply. Was done by measuring of the mass concentration of particles in the recirculation pipe channel, in right branch ESP plant over a longer time interval of 2.5h, so that comparison was fair. As in previous cases, the consideration is taken into account right branch in which they were firstly connected two HVHF power units and then two-50Hz SCR units.

When using two HVHF power is obtained the average value $\hat{C}_{m1} = 80mg/m^3$ of the particle mass concentration, while the use of two, SCR-50Hz power considerably higher concentrations $\hat{C}_{m2} = 400mg/m^3$.

Fig.10 shows the disposition and location of installation triboelectric measuring station for measuring the particle concentration in recirculation channel on TPP "Morava".

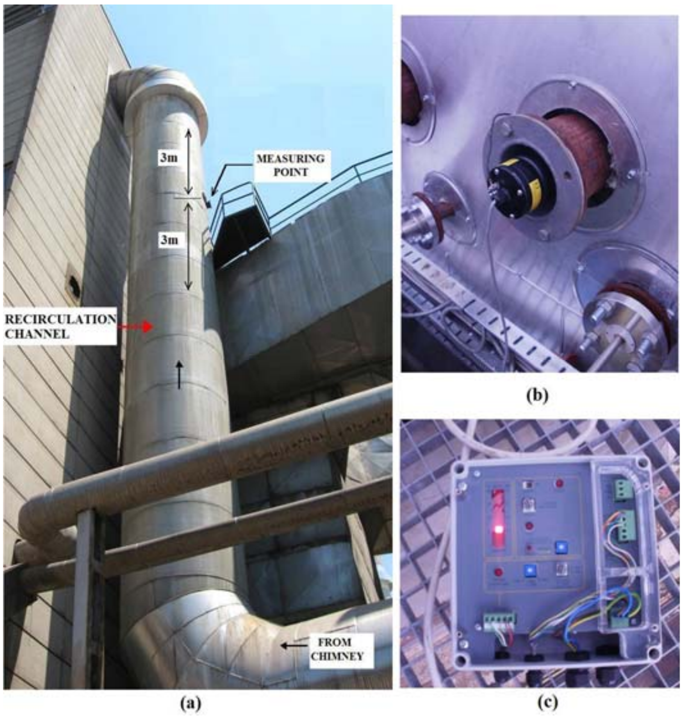

Figure 10. Triboelectric measuring station on TPP "Morava", (a) disposition of recirculation channel, (b) measuring point of triboelectric probe, (c) transmitter and processing electronics.

On Fig.10 (a) is shown disposition of recirculation channel and measuring location of triboelectric probe. Detailed view of this location is shown in Fig.10 (b). Processing electronics of triboelectric sensor is shown in Fig.10(c).

V. CONCLUSION

In the paper are presented operating principles, methodologies, and methods of use triboelectric sensors for measuring the particle mass concentration in flue gas at the ESP station on thermal power plants. It is provided particular emphasis on AC coupled triboelectric sensors. The reason for measuring the AC component is that compared to the DC component the electronics are more sensitive. The AC signal is substantially less affected by influences such as amplifier noise and process parameters, which includes the build-up of process dust on the sensing rod.

In concrete application the TPP "Morava"-Svilajnac, Serbia, are used EMP5 particulate emission monitors (AC coupled triboelectric sensing head with associated electronics), manufacturing *Tyco-GOYEN*. These monitors have proven to be very reliable and satisfactory accuracy, and as such are fully respond to the technological requirements of the ESP plant at TPP "Morava". Also, they have able to detect most particles regardless of composition; they are very sensitive and applicable over a wide range of particulate. In this application they are applied to a range 0-800mg/m³.

The performances of triboelectric sensors are verified by experimental results in the tests and comparisons of HVHF and conventional SCR-50Hz power, concerning to the treatment of flue gases on TPP "Morava".

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