# Continuous Monitoring of Powder Size Distribution using High Temperature ATEX Acoustic Emission Sensors

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**Abstract.** The Principle of Acoustic Emission sensors designed for continuous in-process monitoring is presented. These sensors enable the measurement of acoustic emission on the surface of metallic structures such as rotating machinery in a wide frequency range up to about 1 MHz. Special attention has been paid to the design of the sensors to achieve good and reproducible coupling conditions, a wide and flat frequency response, and insensitivity to low-frequency vibrations, rugged design and small size. A novelty is presented with a high temperature sensor able to work up to 165 °C and the possibility of using the sensor and its coupler in Hazardous areas.

Description of the system for the continuous monitoring of powder particle size distribution, developed by Loccioni illustrates how wideband monitoring of acoustic emission constitutes a powerful monitoring tool. The system has been successfully applied in order to monitor fineness of coal powder burned in coal fired power plants. Basically the proposed instrumentation applies the state of the art of signal processing and neural networks to the acoustic emissions generated by the coal powder while hitting the feeding duct walls, providing percentage values of three different classes of coal fineness.

## 1. Introduction

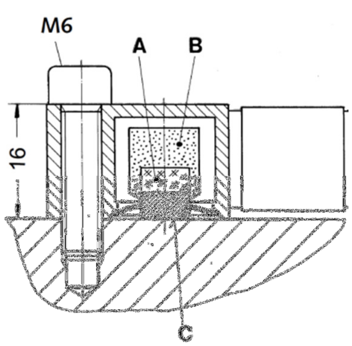
Acoustic Emission measuring chains are especially well suited for measuring high energy surface waves above 50 kHz on the surface of metallic components, structures or systems. Such Acoustic Emission results from flow perturbation, leakage, plastic deformation of materials, crack formation, fracturing, friction and fatigue.
Kistler AE measuring chains have been used for a wide variety of applications for many years. Among them is non-destructive testing and permanent online monitoring of continuous processes in joining assemblies, cutting process monitoring and pipe/valve leakage monitoring.

Recent applications have required an evolution in measuring chain capabilities. Higher temperatures up to 165 ºC are often encountered in power generation monitoring applications. In addition, ATEX certifications are compulsory to work in hazardous environments where explosive gases and dust are always present. Such as in Petro-Chemical industries these measuring chains can be used to detect leaks in piping, valve failure, flow turbulences or even coal particle size monitoring in coal power plants.

## 2. Acoustic Emission Sensor Design

The Kistler 8152C sensor offers a unique mounting and design approach from a typical AE sensor. With AE sensors being used more frequently for NDT, greater temperature range and ATEX/CSA certifications were needed, not only for the sensor but the entire measurement chain.

The 8152C Piezotron AE sensor is used for measuring AE from 50 kHz up to 900 kHz. Its rugged construction makes it ideal for use anywhere from a laboratory environment to the severe conditions in an industrial environment. The piezoelectric ceramic sensing element is mounted on top of a stainless steel diaphragm which in turn is welded to its stainless steel housing (See Figure 1.). The diaphragm coupling surface protrudes slightly below the housing and when mounted, provides a well-defined coupling force. This provides a reproducible coupling of the sensor to the mounting structure and repeatable measurement results (See Figure 2). The sensing element is largely acoustically isolated from the housing due to its design, and well protected from external noise. An internal impedance converter is incorporated in the 8152C AE sensor and provides a low impedance voltage output signal. An internal high-pass filter prior to the impedance converter provides protection from low frequency AE signal and shocks either saturating the impedance converter or causing damage to it.




A… Ceramic piezoelectric element and impedance converter
B… Acoustic backing & internal electronics
C… Coupling diaphragm (preloaded by M6 screw, ¼” screw or magnetic mounting)

**Fig. 1.** Acoustic Emission sensor type 8152C, Cross Section

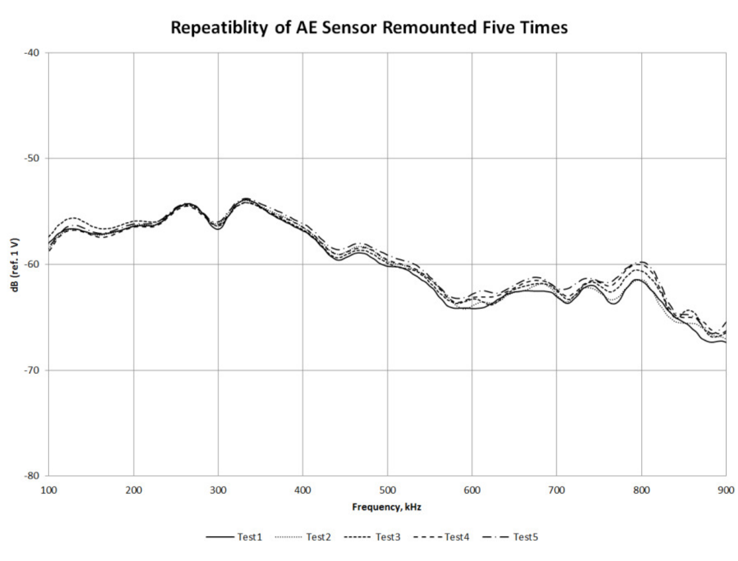



**Fig. 2.** Repeatability of measurements tested and remounted using ¼-20 UNF 2A SHCS

The integral triaxial cable incorporates PFA outer jacket terminating in a pigtail connection. The signal wire, inner shield and drain wire which carry the AE signal are isolated from the outer shield and housing/diaphragm of the sensor. This gives case isolation from the mounting surface which is important in some industrial applications. An option available for even greater ruggedness is enclosing the same triaxial cable in stainless steel braided armour. Due to the high frequency signal content, a low insertion loss is essential for the cable on an AE sensor. The triaxial cable on the 8152C has a loss of 2dB at 900 kHz at a length of 20 meters. Both cable types can be seen in figures 3a & 3b.

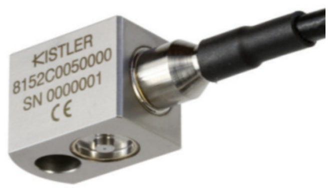




**Fig. 3a.** 8152C with integral PFA jacketed cable (left)

**Fig. 3b.** 8152C with integral stainless steel armoured jacket (right)

In many instances the AE sensor must be used in higher temperature environments. The 8152C was redesigned to have a working temperature of -40°C to +165°C. Figure 4 shows the frequency response at three temperatures. The response has been normalized by the response at 23°C.

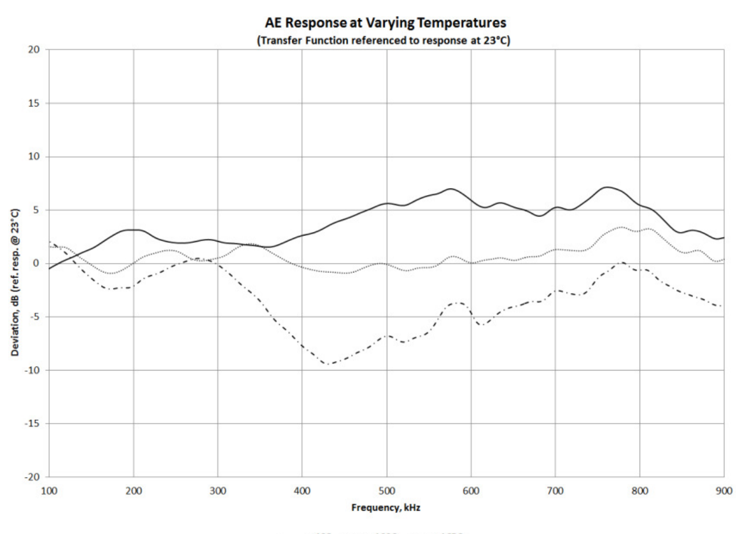



**Fig. 4.** Temperature response curves at various temperatures, normalized be the response at 23°C

ATEX and CSA certifications are essential for many AE applications in hazardous environments. The 8152C is ATEX & CSA Zone 0 and Zone 2 certified. The sample sensor etching is shown in the Figures 5 & 6 below. The two integral cable configurations, PFA jacket and stainless steel armored jacket, are allowable with both Zone 0 & Zone 2 ATEX certified AE sensor. The Zone 0 certified sensor by CSA is also permissible with both cable configurations.  Only the stainless steel armored jacketed cable is permitted on a Zone 2 CSA certified sensor.

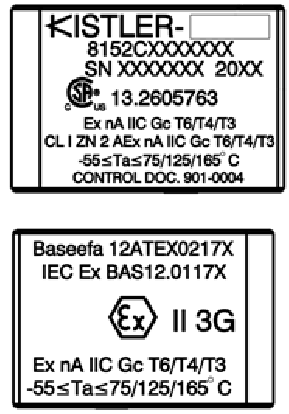




**Fig. 5.** Zone 0 Sensor Etching Detail (2 left)

**Fig. 6.** Zone 2 Sensor Etching Detail (2 right)

## 3. Acoustic Signal Conditioning and ATEX Requirements

For monitoring machining operations, the relatively complex high frequency Acoustic Emission signals need to be processed by the 5125C Coupler. Refer to Figure 7 which shows a block diagram of the measuring chain.

Depending on the amplitude of the AE signal, the gain of the amplifier stage needs to be set. This gain is usually 1, 10, or 100 which sets the range of signal amplitudes to be processed.

A band-pass filter allows processing of the desired frequency range of the AE signal. The right choice of the filters (high-pass and low-pass) affects the signal to noise ratio. Typically, AE signals range between 50 kHz and 1 MHz. By determining the characteristic signal frequency, a narrower frequency range can be set which increases the signal to noise ratio and the repeatability of desired signal detection. This output is buffered and provided typically to a data acquisition system for digital signal processing or it can be view on an oscilloscope or spectrum analyzer. A digital signal processor may be used for assessing filtered AE signals based on statistical methods, amplitude–frequency distribution analysis or exceeding of an amplitude threshold and the frequency of that event (pulse rate).

Root mean square (RMS) processing of the signal is performed which allows monitoring of the signal over longer periods of time. RMS evaluation of the signal has earned industrial application for describing the intensity of the AE signals in filtered frequency bands. The period of time of measurement can be changed by varying the time constant filter on the RMS to DC converter. Typically, the time constant filter ranges between 0.12ms to 25ms. The time constant essentially changes the duration of time that the RMS signal is averaged.

A threshold level detector is a tool used to activate an alarm and the level can typically be adjusted with a potentiometer.  The threshold is set on the RMS signal so that the amplified, filtered and RMS time constant processed signal can used to trigger an alarm or event. Hysteresis is need on this alarm level to maintain the high frequency event for a period of time. Typically this time is set to more than 1 second. The alarm also needs to be isolated so that it doesn't affect the processing of the AE signal.

In summary, a natural high-pass filter characteristic and a wideband sensitivity of the sensors can thus provide the basis for a dependable measuring chain covering a broad range of applications.

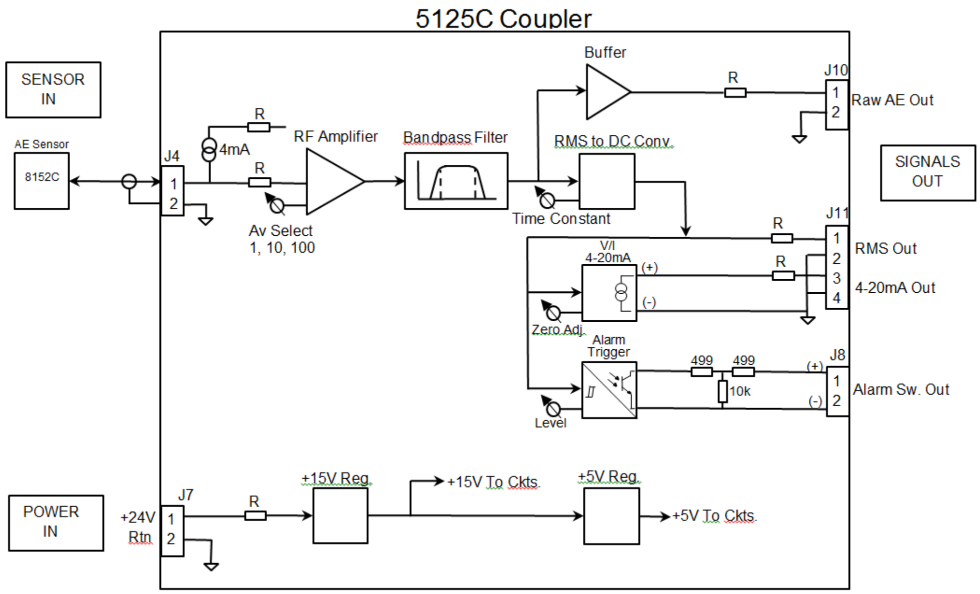
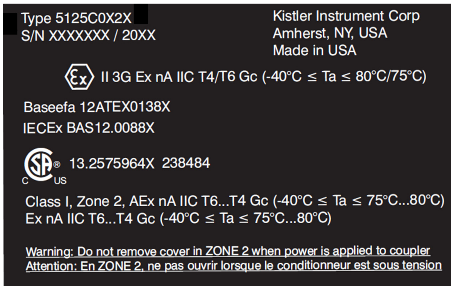



**Fig.7.** AE Measuring Chain (Block Diagram)

Some applications of the AE Measuring Chain require its use in hazardous atmospheric environments. For this reason, ATEX/CSA certification was sought for the entire measuring chain which includes certification for the 5125C Coupler for signal processing and the certification for the 8152C sensor as described previously. The certification was granted, however, the +24VDC supply on the 5125C Coupler needed to be reduced to +15VDC to limit the voltage and current in hazardous area and the raw AE output had to be removed so that the 5125C coupler could be certified as intrinsically safe. The intrinsically safe ATEX/CSA approved 5125C Coupler used for signal processing are shown in Figure 8 along with the certification labels in Figure 9a & 9b.

**Fig.8.** ATEX/CSA approved 5125C



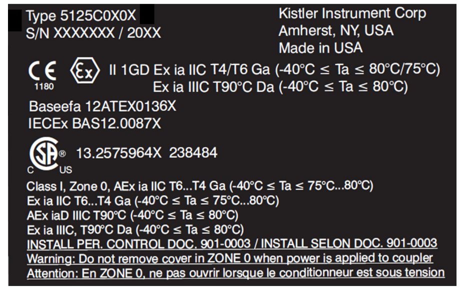
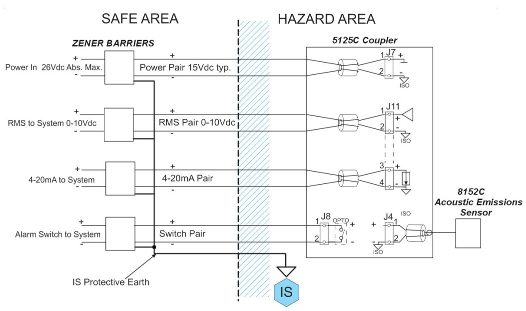
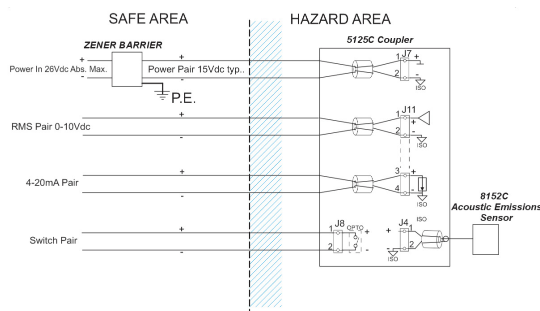




**Fig.9a.** 5125C ATEX Zone 2 Coupler Label (left)

**Fig.9b.** 5125C ATEX Zone 0 Coupler Label (right)

There are measuring chain configurations for hazardous areas shown in Figures 10a (Zone 0), Figure 10b (Zone 2), and Figure 10c (Sensor Only in hazardous area). Setting up these measuring chains as shown ensures safe operation in a hazardous area. The Zener Barriers shown in these diagrams provide limits for the voltage and current provided to a hazardous area which provides an intrinsically safe set-up. It should be noted in Figure 10c that the high frequency Zener barrier needs to operate up to 1 MHz without significant signal losses.



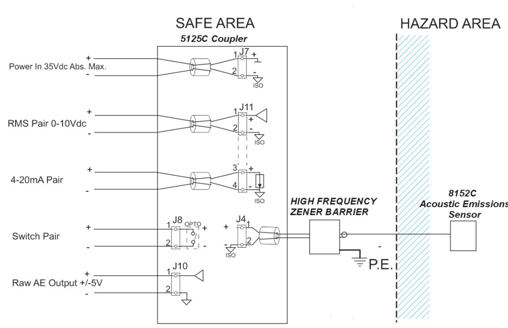




**Fig. 10a.** ATEX/CSA Hazardous Area Installation for Zone 0 (upper left)

**Fig. 10b.** ATEX/CSA Hazardous Area Installation for Zone 2 (upper right)

**Fig. 10c.** ATEX/CSA Hazardous Area Installation for Sensor Only (lower)

## 4. Acoustic Emission Applied to Continuous Monitoring of Powder Particle Size Distribution

### *4.1 Case Description*

Continuous monitoring of particle size distribution (PSD) of powders, also named either granulometry or fineness, has always been a critical challenge in processes control. Coal, chemicals, cement, and raw materials are some examples of powders commonly used or produced in the process industry. The ability to continuously monitor particle size is critical in order to control and optimize the quality of fuel and products. To this aim, the Italian company Loccioni has developed a system named POWdER which is able to monitor particle size distribution based on acoustic emission measurements. In particular, acoustic emission has been revealed to be a powerful tool in the monitoring of coal powder fineness. Indeed coal is one of the most popular fuels used in energy, cement and steel production. For each of these processes it is very important that the coal is reduced into fine powder according to specific limits over the following coal power plant thresholds:

- *Retained 50 mesh*, which accounts for largest particles (particle size larger than 300µm)
- *Through 200 mesh*, which accounts for the smallest particles (particle size lower than 75µm)

In order to obtain optimal burning conditions inside the combustion chamber, to reduce fuel consumption and emissions, coal powder must have *retained 50 mesh* of less than 1%, and *through 200 mesh* of greater than 60%.

### *4.2 Acquisition System Description*

The test results shown in this paper were obtained using a POWdER system installed on a 330MW coal fired power plant. The measurement system is made up of five measuring points, placed on five different feeding ducts of the boiler system and consists of the following:

1. A single control unit;
2. Five acquisition units (i.e. measuring points), one for each pipe to be monitored

For safety reasons the control unit and acquisition units have been placed in two different areas of the plant. Since the area close to the burners is where the sensors are installed, it is classified as ATEX Zone 2.

The control unit, placed in a safe area, is enclosed in a cabinet containing acquisition boards, a PC, a power supply and communication devices. Acquisition units are installed in the ATEX Zone 2 area. Each acquisition unit consists of an acoustic emission sensor, a temperature sensor, a sensor mounting base and a junction box where the signal conditioning is enclosed. The measuring chain used for each acquisition unit is the one described in Figure 10c. In fact, the particular quantification algorithm embedded in POWdER works directly with the 'raw AE out' signal as opposed to the 'RMS out' signal.

AE sensors are placed directly on the wear plate just before the burner, in junction with the feeding duct elbow. Contact between the sensor and the plate is maintained magnetically by means of a magnetic mounting base specifically designed for the sensor. The mounting base acts as a waveguide and is used in order to protect sensor from dust deposits and temperature overload that could reach up to 200°C in case of burner failure.

In this application the usual working temperature on the external surface of feeding ducts can vary from 40 °C to 80 °C. The general layout of the control unit and the acquisition unit is shown in Figure 11.

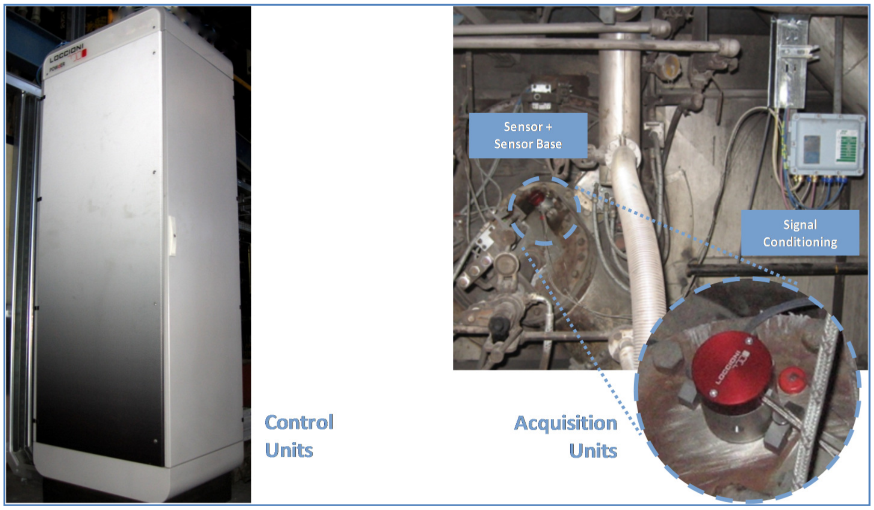



**Fig. 11.** General Layout

*4.3 Measuring Principle*

According to Hertzian impact theory, energy released by a particle impinging on the surface of a rigid body, generates a system of elastic waves within the body formally equivalent to a source of acoustic emissions. In [4] it has been demonstrated that by coupling both acoustic emission and Hertzian impact theory it is possible, at least theoretically, to find a relationship between acoustic emissions emitted by a single particle hitting on a metal surface and its size. Experimental and theoretical works about particle sizing by means of acoustic emissions have been carried out since 1977 [5].

Some of the models available in literature rely on measuring the beat frequencies from different resonance frequencies of particles with varying diameters. Some other models rely on statistical analyses of time domain signals (average duration of a beat event, average time between zero-crossing) instead. However an analytical approach for the most general case of several arbitrarily shaped particles hitting on an irregular metal surface (i.e. the condition inside the feeding pipes of a power plant) has never been carried out because it would be too complex. In order to overcome this great limitation, a suitable proprietary algorithm has been developed at Loccioni by applying advanced system identification techniques to acoustic emissions using a grey box approach. For additional information about system identification see [6].

In particular, POWdER embeds neural network models in order to correlate the detected acoustic emission signal to fineness measurements. Neural networks have to be trained (i.e. calibrated) on the particular pipe to monitor. This procedure is essential for the correct functioning of the system and it distinguishes all the effects on acoustic emission signal not directly related to coal particle size, such as geometry, wear of components and environmental noise. In practice a mathematical model is created for every pipe that is monitored. This allows the highest reliability and robustness of the measurement to be achieved. Figure 12 shows the conceptual layout of POWdER Algorithm.

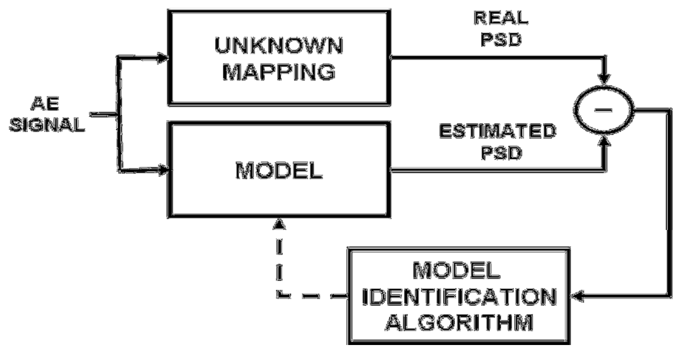



**Fig. 12.** Conceptual layout of POWdER Algorithm

*4.4 System Calibration*

During neural network training, the fineness is measured using the *reference manual method* (sample and sieve) along with the AE signals. For each pipe approximately 270 observations with 50 different grinding regimes (i.e. different particle size distributions) have been performed. Approximately 230 of those observations have been used as a training set for the neural network and the rest have been used as a validation set.

From the acquired AE signals, a small set of significant data, called *features,* correlated with the PSD is then extracted. The *features* extraction is performed to minimize the influence of all other process variables not directly connected with particle size. A learning algorithm is used to map the *features* vector into the corresponding PSD measure. Fineness measurements made with the *standard manual method* are then used as targets for the neural network training. Each target value has been averaged on two powder samples.

Once the mathematical model has been generated, the main neural network outputs then represent the *retained* percentages of *50 mesh* and the *through* percentage of *200 mesh* already presented in the paragraph above.

*4.5 Results and Discussion*

After the neural networks training, it was then possible to check the accuracy of the measurement performed by POWdER. By comparing results with measurements from the *standard manual method*, the accuracy is obtained. For each pipe, the comparison has been carried out on 30 observations over six casual particle size distributions within a range around the normal working condition of the power plant (Table 1).

| Threshold | Variation Range |
|---|---|
| 50 mesh retained | 0% - 3% |
| 200 mesh through | 40% - 70% |

**Table1.** Normal working condition of the power plant

The measurement accuracy has been evaluated in terms of Root Mean Square Error (RMSE) with respect to the reference values measured through manual sampling. The repeatability of the single measurement is defined as Standard Deviation (SD) calculated over a period of 20 minutes under the same working conditions.

Shown below are the results of fineness measurements in terms of *50 mesh* and *200 mesh* for some of the pipes monitored.

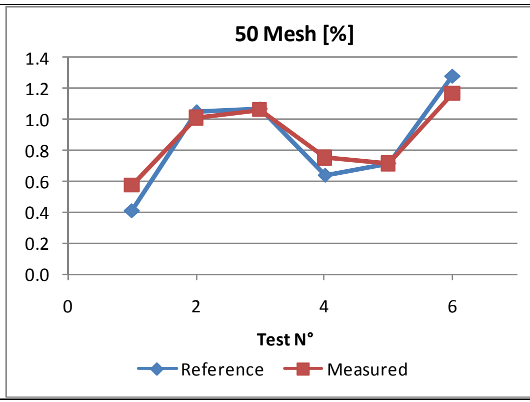



**Fig. 13. :** Pipe 3 validation on *50 mesh*

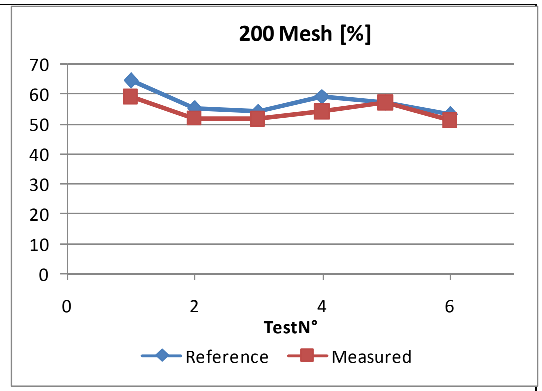



**Fig. 14.** Pipe 3 validation on *200 mesh*

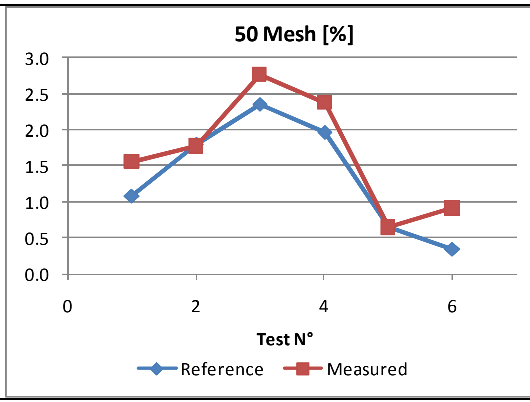



**Fig. 15.** Pipe 4 validation on *50 mesh*

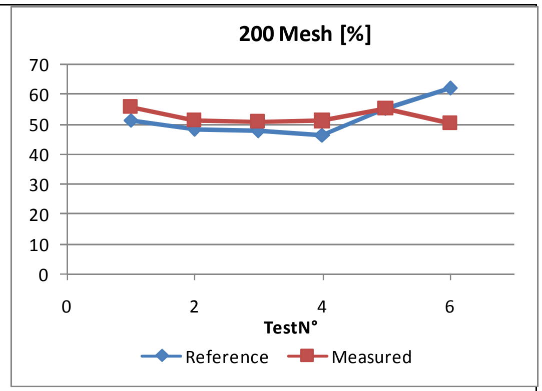



**Fig.16.** Pipe 4 validation on *200 mesh*

As it is possible to see from Figure 13 to Figure 16, values measured by POWdER fit well with reference data obtained from the *standard manual method* sampling. Trends are clearly visible and absolute values are also well predicted. A general overview of the results is shown in Table 2.

| | ***50 mesh*** | | ***200 mesh*** | |
|---|---|---|---|---|
| | **RMSE** | **SD over 20 minutes** | **RMSE** | **SD over 20 minutes** |
| **Pipe 1** | 0.1345 | 0.0235 | 4.3239 | 0.4546 |
| **Pipe 2** | 0.4061 | 0.0453 | 4.5160 | 0.3082 |
| **Pipe 3** | 0.0539 | 0.0373 | 2.2412 | 0.3477 |
| **Pipe 4** | 0.2722 | 0.0659 | 6.5850 | 0.6618 |
| **Pipe 5** | 0.0488 | 0.0204 | 2.4652 | 0.423 |

**Table2.** Normal working condition of the power plant

## 5. Conclusions

This paper has shown us that usage of Acoustic Emission measurement techniques, along with many other applications, allows for accurate monitoring of particle size. Such a task represents a challenge within process control, fuel optimization and other products quality. The goal of optimization of burning conditions, reduction of fuel consumption and emissions was achieved. The investigations performed with POWdER have shown that the coal powder fineness can be directly correlated with the Acoustic Emission signal obtained through the ATEX Zone 2 certified KISTLER measuring chain. Comparison between mathematical models and POWdER values correlated very well. Such a high level of accuracy in real-time monitoring of coal particle size has allowed the operating staff of the power plant to adjust the coal grinding parameters while at the same time, obtaining the desired combustion optimization and a non-negligible coal consumption saving.

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