Practical continuous emissions monitoring to reduce particulate emissions from industrial plant and to satisfy regulatory requirements

Author: William Averdieck, PCME Ltd
williama@pcme.co.uk

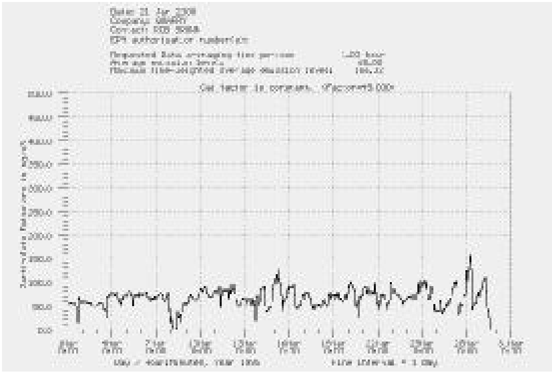
1 Introduction

Reducing particulate emissions from industrial processes is a common goal for industrial plant operators across the industrialised world. A significant and growing number of industrial organisations understand that continuous monitoring plays an increasing role in reducing emissions since it provides the feedback to ensure dust arrestment plant continue to operate to optimum performance while reducing operating costs.

Plant operators are also faced with the issue of satisfying regulatory emission monitoring requirements are naturally searching for robust, efficient and cost-effective solutions. This paper provides an overview of how Electrodynamic, Dynamic Opacity and light scatter instruments can provide a solution to particulate monitoring requirements and describes the technology used in such instrumentation. It provides an overview of global regulatory drivers for particulate emission monitoring and due the importance of product approval schemes discusses regulatory requirements in the UK, Germany and the USA where such schemes are in operation.

2 What Is Continuous Particulate Emission Monitoring

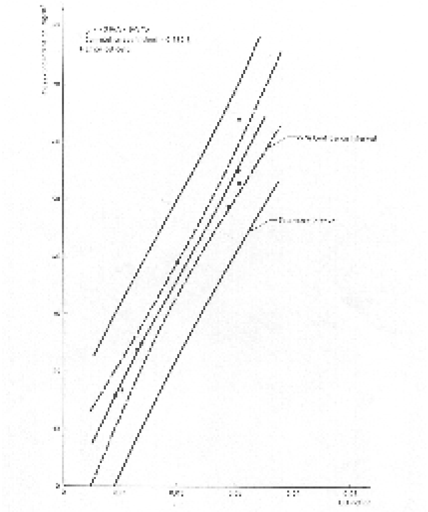
A continuous particulate emission or concentration monitor provides an output calibrated to show particulate levels in mg/m^3 on a continuous basis. This output is generally recorded for reporting and analysis purposes.



Typical report from a PM-CEM

The performance of concentration monitors is application specific, since all instruments measure a parameter which is related to mass rather than mass itself. The acceptability of an instrument is defined by how well its output relates to dust concentration determined by isokinetic sampling (a gravimetric extractive technique) over a range of dust concentrations over time. Reflecting that there are systematic errors in isokinetic sampling (typically 10%), the correlation between instrument output and isokinetic result is assessed in terms of a statistical analysis. For example ISO-10155 (the international performance standard for particulate monitors) defines a minimum allowable correlation coefficient of 0.95 and limits on other statistical limits such as confidence and tolerance interval.

Concentration monitors are typically recalibrated at least once a year by reference to an isokinetic test, since this is the only way of checking the calibration in mg/m^3. More frequent quality control checks are performed to satisfy regulatory requirements to ensure the instrument is working properly. These are typically implemented as automatic zero or span checks which simulate to the instrument the parameter being measured.



Performance Curve for Particulate Monitors

For high impact emission sources the procedures for calibration and on going quality assurance are defined in specific standards. For example in Waste Incineration Processes in Europe must apply the standard EN-14181 which provides exacting standards for calibration using 15 reference points over 3 days (refered to as QAL2) and statistical analysis of the zero and span checks (QAL3) with the objective of knowing that the measurements are made with defined uncertainty.

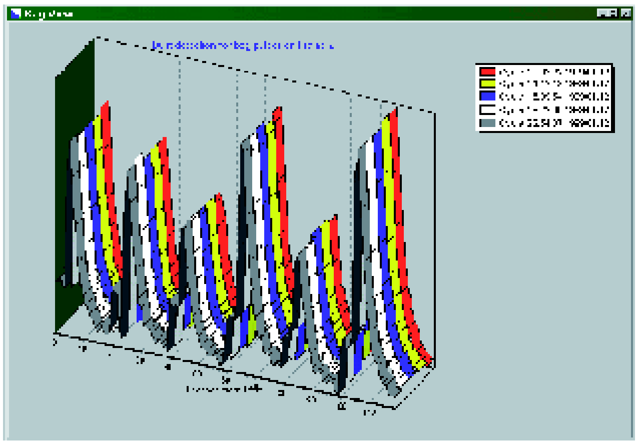
In addition to continuous particulate emission measurement there are other pragmatic forms of continuous monitoring. These include **qualitative monitoring** in which the objective is to provide feedback on the performance of an arrestment plant and this can be accomplished by monitoring the trend of particulate levels rather than the absolute levels. Regulators usually define what quality of correlation they accept between instrument response and dust concentration if they are using qualitative monitoring as a basis for regulatory control.

It should be noted that continuous particulate measurement is replacing continuous opacity or colour monitoring. Significantly, environmental emission regulations have changed to specifically limit the particulate concentration in mg/m^3 and kg/year rather than the colour, since in modern industrial processes the environmental impact of a process is related to the quantity of particulate rather than the colour of the emission. Also many emissions while still being finite, are colourless and below the minimum detection limit of Opacity instruments. As regulations have moved to specifying limits in mg/m^3 instead of colour, other types of instruments including those using Dynamic Opacity (Scintillation), Light Scatter and Electrodynamic technology are often more suitable for making this measurement than Opacity type instruments.

2 Reducing emissions from industrial processes by effective particulate monitoring

In general dust arrestment plant is installed after industrial emission sources to reduce particulate levels. While particulate may be controlled by Electrostatic Precipitators, cyclones, scrubbers and filters, the trend is to install filter type arrestment plant since they have higher collection efficiency are more efficient, create no water waste and can be designed to operate even at elevated temperatures. Particulate monitors are fitted after the arrestment plant to detect and monitor for malfunction or sub optimal performance of the filter system which will otherwise undetected lead to increased particulate levels.

Particulate monitors can be used to pre-warn of imminent problems in filter systems by monitoring the dynamics of dust during the automatic cleaning cycle of a bagfilter. High peaks in dust are associated with the cleaning of a bagrow with a failing filter bag and therefore by synchronising the instrument to the cleaning controller , maintenance personnel can easily determine which bagrow requires maintenance before a major incidence occurs.



In addition in large multi-compartment bagfilters, multi-probe dust monitoring systems can be used to detect and isolate the compartment causing elevated emissions which again allows emissions to be controlled.

3 Overview Of Legislative Requirements for continuous particulate monitoring

It is now widely understood that increased particulate levels have a direct impact on human health problems and global pollution. The health problem is particularly apparent with small particles (which are absorbed by the human lung and particles with high carbon and metals content). Hence Environmental regulators worldwide stipulate emission limits for particulates. In addition many regulators require continuous particulate monitors to be fitted to industrial processes for the same two reasons:

- To enforce particulate emission limits in mg/m^3 and kg/year.
- To provide feedback that pollution abatement equipment is working correctly.

The overall trend is that continuous particulate measurement is required in the both large stacks and those with environmentally sensitive emissions. Other types of continuous particulate monitoring such as qualitative and broken bag detection can be required in smaller processes.

The regulatory situation in the UK and Germany is of international interest, since both countries have adopted approval scheme for particulate monitors reflecting national and international regulatory demands. The US is also moving in this direction. A review of the requirements in these countries is therefore given below.

United Kingdom

Continuous monitoring of particulate is widely implemented in the UK with divisions between the types of monitoring often being decided on stack air flow and the type of process. Only in combustion processes do additional Ringelmann limits remain. With the implementation of the Environmental Protection Act in 1990, continuous monitoring of particulate was required in the majority of industrial stacks since it was considered BATNEEC (Best Available Technique Not Encurring Excessive Cost).

The regulatory focus in the UK is on 3 levels:

1) Like in other European countries, Incineration, Cement Kilns (burning Waste) and Large Combustion Plant fall under the European Waste Incineration Directive (WID) and large Combustion Plant Directive (LCPD). These plants are regulated by the Environment Agency and must meet emission limits and monitoring protocols defined in the EU Directives. Continuous monitoring is to be done with the measurement uncertainty assessed to be less than that permitted by the relevant Directives. CEM systems are being upgraded in the period 2005- 2008 to meet these new requirements which are detailed in the European standard EN-14181. This standard sets procedures for instrument certification (QAL1/MCERTS), calibration (QAL2) on going quality assurance (QAL 3) and an annual audit (AST)

2) Larger industrial processes (eg: chemical plant, steel mills, Aluminium smelters, large mineral plant) are regulated under PPC regulations (UK implementation of the EU directive on Integrated Pollution and Control) by the Environment Agency. Typically, continuous measurement is required but for smaller emission points broken bag detection is sufficient. Very few industrial stacks have no continuous monitor.

The UK Environment Agency provides incentives (in the form of less regulatory attention) to industrial operators that use continuous monitoring instrumentation which are MCERTS approved. MCERTS, is a certification scheme which has operated in the UK since 1999. This Scheme defines standards to which continuous monitors must perform. Instruments obtain a certificate for specific processes and measurement ranges based on a laboratory and three month field test overseen by an independent test body (SIRA). ISO-10155 is used as a basis for the test standards against which particulate monitors are tested. Measurement and qualitative instruments are covered by this scheme.

3) Smaller (Part B) industrial processes (eg: Roadstone plant, foundries, animal feed plant, Combustion plant <50MW) are regulated for air emissions by local authorities and regulations require;

- Continuous measurement in stacks with air flow greater than 300m³/min
- Qualitative monitoring and broken bag detection in stacks with air flow greater than 50m³/min
- No monitoring in stacks below 50m³/m

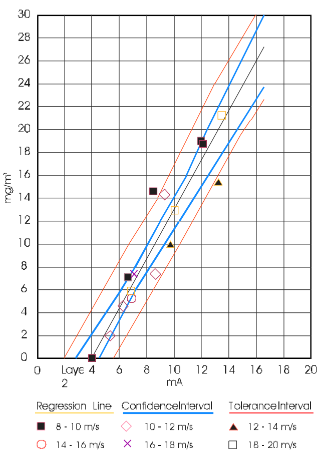
Germany

Regulatory limits are based on Particulates rather than Opacity although there are requirements for continuous Opacity instruments as a qualitative measurement in certain combustion processes. Continuous measurement is required based on local air pollution issues (ie stack is close to residential area) or on stacks when the total mass emissions of particulate is likely to exceed defined limits. These limits depend on the toxicity of the particulate. As in the UK and other European countries Incineration and Power plant falling under the WID and LCPD directive must fit continuous monitors according to EN-14181

Specific national regulations impacting the use of continuous particulate monitors are:

BImSchV 13: Combustion Plant > 50MW
BImSchV 17: Incineration Plant
BImSchV 27: Qualitative monitoring of particulate after filter plant

A type approval scheme exists in Germany. This scheme is widely respected, due to the importance placed on field testing and quality assurance issues (such as instrument checks). Particulate monitors are tested by independent test authorities (eg TUV) against standards and for measurement ranges defined by each of the above regulations. Test certificates note any restrictions on the use of an instrument. The performance curve for an instrument certified under BImSchV 27 is shown below.



United States

Historically the UK and Germany have led the US in terms of experience with particulate monitors, since US emission limits and monitoring methods have been specified in terms of Opacity (colour). However particulate monitoring is now becoming a regulatory issue with the shift towards lower concentration limits below which Opacity cannot be applied and to processes where colour is irrelevant. The following regulatory changes resulting from the Clean Air Act 1990 amendments are also stimulating needs for particulate monitors:

- Many industrial processes must apply new MACT (Maximum Achievable Control Technologies) rules. Many of these rules especially in the metals industry require that baghouses be fitted with appropriate filter failure monitors. Qualitative Particulate monitors are used to satisfy these requirements
- Title V plants (the major metals, chemical, mineral and combustion processes) are required under the new CAM (Compliance Assurance Monitoring) regulations to develop a method to ensure the continuous compliance of their particulate arrestment plant (eg Baghouses and Electrostatic Precipitators). It is likely **qualitative particulate monitoring** will be chosen by many sites as a pragmatic solution to this new requirement when Title V permits are renewed.
- In the future EPA may require **Continuous Particulate Measurement or PM CEMS** (Particulate Matter Continuous Emission Monitors) on Incinerator stacks While a new standard PS-11 exists, this is not as yet required. PS-11 applies the same performance approach as ISO-10155 and as such is similar to the UK and German type approval scheme. However, a significant difference is that each PM CEM will require validation in the specific stack in which it is being used.

4 Use Of Dynamic Opacity (Scintillation), Light Scatter And Electrodynamic Technology In Particulate Monitors

Regulatory demands for particulate monitors have stimulated the development of a range of instruments for different types of application. Of the eight different technologies used in commercially available particulate emission monitors, Opacity, Dynamic Opacity (Scintillation), Light scatter and Electrodynamic are used in the majority of new installations due to their regulatory acceptance and their suitability as pragmatic solutions to monitoring requirements.

Opacity is historically well known but is less used today than in the past. This is due to industrial progress in that typical emission levels and emission limits are below the minimum detection limit of this technology. Opacity instruments are therefore limited to emissions above 50mg/m3/m (large power plant) but not applied to metals, minerals and chemical processes where bagfilters are often fitted which control emissions below 10mg/m3

The balance of this paper concentrates on the use of Dynamic Opacity (Scintillation), Light scatter and Electrodynamic technology for particulate measurement since these are the core technologies used by PCME. Instruments using these techniques are installed in over 10,000 applications worldwide.

For reference, the full range of technologies used for particulate monitoring in certain applications are:

- Light attenuation (Opacity)
- Dynamic Opacity
- Back/Side Scatter
- Forward Scatter
- Oscillating Filter (Vibrating tapered element)
- Beta Attenuation
- Triboelectric

4.1 Dynamic Opacity (Scintillation)

Principle of Operation

Like Opacity Monitors, Dynamic Opacity (Scintillation) monitors measure the effects of particles on a light beam transmitted across the stack. However, the essential difference is that they measure not only the beam intensity as such, but the ratio of the temporal variation in intensity to the intensity. This intensity variation derives from the statistical variations in the distribution of particles in the air-stream. The higher the concentration of particles, the greater the range of variation. Empirical results confirm a simple linear relationship between scintillation and dust concentration and show that with zero dust there is no scintillation (ie the instrument has a true zero, unlike Opacity devices). The term Dynamic Opacity or Scintillation is related to the dust concentration as follows:

$$\text{Dynamic Opacity} = \frac{\text{Variation in intensity}}{\text{Intensity}} = K \times C$$

Where C is the dust concentration and k is an empirical constant for the particle physical properties.

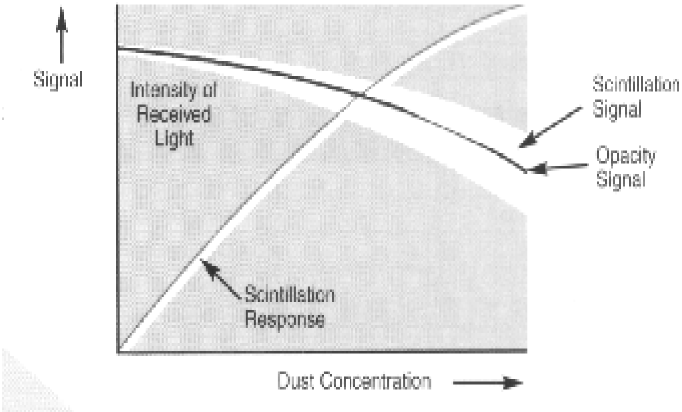


Diagram showing Dynamic Opacity vs concentration

Practical Considerations

1. One of the most important characteristics of the Dynamic Opacity (Scintillation) technique is its tolerance to instrument contamination. A Dynamic Opacity (Scintillation) monitor will continue to function without error even when its lenses are heavily coated with dust. As a result there is no need to fit large air purge blowers to the system. In high dust loading applications, the transmitter and receiver are connected to a supply of instrument air (using 1 CFM of air) to stop the light beam being completely obscured by catastrophic build-up. Provided sufficient light is getting through for the instrument to make a measurement (at least 10% of clean instrument amount), its response is unaffected by any contamination since the numerator and denominator of the ratio are affected by the same amount.

2. The Dynamic Opacity (Scintillation) instrument is not significantly affected by the absolute alignment between the transmitter and receiver, since like contamination this effects the numerator and denominator of the ratio by the same amount. As a result the adjustable mounting alignment of the

instrument can be set by eye sight on first setting up the instrument.

3. The instruments are generally single pass since there is no need to increase the path length due to concerns on detection level. Unlike the Opacity technique the instrument measures no signal when there is no dust and, therefore, it is possible to increase the signal to noise ratio. In practice this means the instrument can detect low dust concentrations as low as 2.5mg/m^3/m (at least 10 x better than an Opacity device).
4. Relevant light and electronic automatic zero and span checks can be built into the instrument to check for instrument integrity. As with all types of in-situ devices, these do not check for changes in particulate calibration.
5. There are also certain applications in which measurements must be made in terms of Opacity and Ringelmann (colour) characteristics as well as mg/m^3. To allow for such applications, Dynamic Opacity (Scintillation) monitors can be switched into Opacity measurement mode.

Their limitations are as follows:

- The calibration of a Dynamic Opacity (Scintillation) instrument will shift if there are changes in parameters affecting the attenuation of light by a particle. These include particle size, shape and particle material.
- The calibration is also affected by changes in process conditions affecting the statistical distribution of the particles. In practice this means that the start-up and shut down of certain processes may not be accurately monitored by Dynamic Opacity (Scintillation).
- Like Opacity the scintillation response is affected by water vapour and refraction due to thermal gradients. This can result in an offset which increases the minimum detection level to be above 2.5mg/m^3.

In practice Dynamic Opacity (Scintillation) instruments can be a more reliable alternative to Opacity instruments where regulations require particulate measurement as opposed to Opacity. They are often used in combustion applications and other industrial processes with large stack discharges from an Electrostatic Precipitator or Bagfilter. Utilities throughout the industrialised world are using Dynamic Opacity instruments manufactured by PCME..

Approvals

Dynamic Opacity (Scintillation) instruments are approved for regulatory use in both UK and Germany. The SC-600 manufactured by PCME holds an MCERTS approval for particulate measurement in the range of 0-150mg/m^3 . Processes for which it is approved include Electrostatic Precipitators and/or Coal Fire Utility boilers.

4.2 Electrodynamic Instruments

Principle of Operation

In this system, proprietary to PCME, a grounded sensing probe is installed across part of the stack and the resulting current from charged particles passing the sensor analysed and measured. The dc current produced by particle collisions on the rod is eliminated by ac filtering techniques. The instrument conditions the remaining alternating signal produced by charged particles inducing charge flow in the sensor rod as they pass it and analyses and measures the frequency component thereof. Since the signal is not dependent on particle collisions, the related problems of rod contamination and velocity dependence by which triboelectric are limited, are minimised.

In applications where the particle charge, particle size and particle distribution remain constant the resulting alternating current is proportional to dust concentration. These instruments can be calibrated in mg/m^3 by comparison to the results of an isokinetic test.

Practical Considerations:

- The sensor rod can be completely insulated to extend operation into humid (drier) applications.
- The sensor rod can tolerate contamination without reduction in performance since the measurement signal derives from induction rather than collision.

Technical limitations are as follows:

1. The use of Electrodynamic technology for particulate measurement requires applications with

predictable particle type and pre-charge, non-condensing conditions and a minimum velocity of 5m/s. There are only minor effects of changing velocity if the velocity is greater than 8m/s.

2. The standard instrument cannot be used for measurement with the presence of water droplets, however, is often used in non-condensing humid applications (after driers), since it can discriminate between solid particles and water vapour.
3. The technology is only suitable for indicative monitoring in applications in which the pre-charge on the particle is likely to change. In practice this covers Electrostatic Precipitators (EP) and combustion applications where charge on the particle may be changed by EP condition and flame ionisation effects respectively.

Electrodynamic instruments are used to satisfy both measurement and qualitative requirements on Bagfilters in the metals, mineral and chemical industries. Their adoption in UK is extensive and their use in Europe, US , Japan and Australia is widespread. Regulatory approvals exist for qualitative and measurement instruments in both the UK and Germany.

Approvals

PCME's electrodynamic instruments have been approved for measurement of particulate in the ranges of 0-15mg/m^3 and 0-30mg/m^3 in Germany and UK respectively. The UK MCERTS Class 4 approval and German BImSchV 17 approval are for bagfilter applications and are relevant to many applications where particulate monitoring may be required.

4.3 Light Scattering

Principle of Operation:

Light scattering particulate monitors make use of the physical effect that small particles similar in size to the wavelength of light used (ie O.5micron), scatter or reflect a light beam in all directions. This phenomena is observed by the human eye when observing sun rays illuminate suspended dust in a darkened room. Light scatter instruments are not concerned with transmitted light and the minimum detection limit is significantly better than Opacity instruments. The receiver measures the amount of light reflected (scattered) from the direction of incidence by the particles. Importantly instruments have different characteristics depending upon the specific scatter or reflection angle chosen for measurement. This behaviour is well predicted by MIE and Raleigh scattering theory.

In-situ instruments are generally categorised as either back/side scatter instruments or forward scatter instruments according to their scattering angle

Forward Scatter Devices

A forward scatter device measures the light that is scattered at a small angle from the angle of incidence .This angle is typically in the range of 5' to 15'. The response is proportional to dust concentration for a given set of particle properties and can therefore be calibrated in mg/m3.

Practical considerations are:

- Forward scatter instruments are playing an increasing role in the particulate measurement market. Importantly their calibration is mainly unaffected by changing shape and type and the instruments have sufficient resolution to measure emissions below 1mg/m3 (compared to a minimum 50mg/m3/m detection limit for opacity instruments)
- Forward scatter devices have better sensitivity than back scatter devices so it is possible to use LEDs and diode lasers as sources of light.
- The receiver can be mounted either on the far side of the stack or in the case of a probe based instrument at the far end of the measurement cell embedded in the probe.
- Since measurement is occurring at small angles to the incidence it is very important to shield the receiver properly from directly transmitted light
- Air purges are required for optical surfaces although compensation for dust accumulation can be made by separately measuring changes in directly transmitted light.
- Instruments with multiple detectors at different scattering angles can be used to determine particle size..

Limitations of forward scatter instruments are

1. Calibration is dependent on particle size although this cross sensitivities are less than with back scatter devices.
2. In-situ light scattering instruments cannot differentiate between water aerosols and solid particles
3. The measurement volume is relatively small especially in probe type designs. Appropriate instrument location is therefore important.

There are also extractive light scatter instruments in which a sample of flue gas is sampled under isokinetic conditions and then passed into an external light scattering chamber. A forward light scattering technique is normally used in the chamber and a heater unit can be fitted before the chamber to evaporate and eliminate water from a wet or humid application. The same problematic issues of sample handling are as relevant with these instruments as for Beta attenuation devices. Extractive light scatter instruments with a heated chamber have German regulatory approval for wet applications.

Approvals

Light scatter instruments are approved for emission measurements both under the MCERTS and TUV approval scheme. PCME has developed a light scatter instrument specifically to meet the quality assurance issues arising from the QAL1 (instrument approval) and QAL3 (on going instrument quality assurance) of the standard EN-14181 (EN-13284-2 for particulate)..As such the instrument is suitable for incineration, cement kiln and power plant applications falling under these new standards.

5 Summary

Continuous particulate monitoring instruments play an important role in air pollution control by providing industry with information to control arrestment plant as well as provide proof of emissions verses time. The regulatory approach is similar in most parts of the world with requirements for continuous measurement and qualitative monitoring of arrestment plant dependent on the type of plant and size of the process. Certification schemes are in place in UK and Germany which assist regulators and industry have confidence in results from continuous monitors. There are a number of techniques used for monitoring particulate and Dynamic Opacity (Scintillation), Light scatter and Electrodynamic instruments are techniques used in instruments manufactured by PCME. These instruments overcome the resolution and reliablity limitations of traditional opacity and satisfy many of the requirements in measuring emissions from Electrostatic Precipitator and Bagfilter arrestment plant.

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