Continuous Particulate Emission Monitoring with Dynamic Opacity (Scintillation) and Electrodynamic Instruments to Satisfy Concentration and Mass Emission Regulatory Requirements

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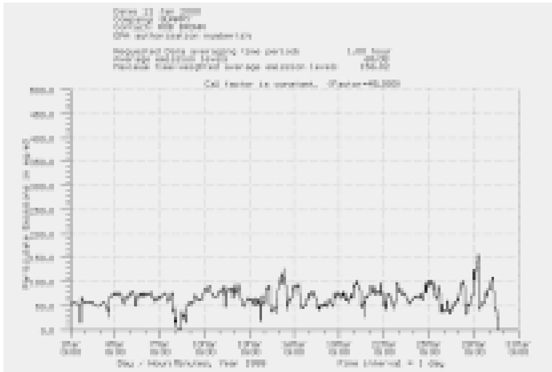
1 Introduction

Plant operators 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 and Dynamic Opacity instruments can provide a solution to particulate monitoring requirements including concentration and Mass Emission monitoring 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.

The paper also describes a flexible, industrially hardened monitoring network, which for large sites, provides an efficient means of connecting a large number of continuous particle monitors to a central location and collating data for easy interpretation and reporting. Particulate emission technologies supported by the network include Electrodynamic (suitable for monitoring baghouses with varying velocity), and Dynamic Opacity (suitable for Electrostatic Precipitators). Sensor types also include Particle Emission Monitors, particulate indicative instruments and broken bag monitors.

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

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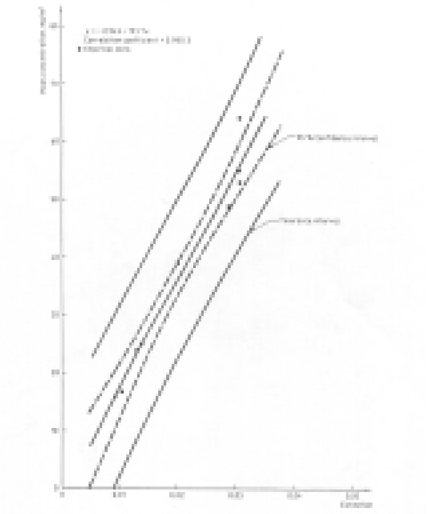
automatic zero or span checks which simulate to the instrument the parameter being measured.



Performance Curve for Particulate Monitors

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. Also available is broken **bag detection** in which an alarm is activated should a significant increase of particulate loading be detected, indicating a failure of the pollution arrestment plant.

A new area of regulatory concern is the total mass of emissions from a stack. **Continuous Mass Emission instruments** combine a continuous concentration measurement with on-line measurement of stack velocity. The derived output is normally expressed in terms of kg/day or g/hour and this is totalised to report the total mass emissions over for example a year.

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) and Electrodynamic technology are often more suitable for making this measurement than Opacity type instruments.

3 Overview Of Legislative Requirements

Environmental regulators worldwide require continuous particulate monitoring 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. Mass emission monitoring is less universally applied to particulate measurement, but becoming an issue with the advent of emissions inventories and tradeable permits.

3.1 Concentration Measurement

There is increasing reliance on continuous particulate concentration monitoring in most parts of the industrial world including Australia, reflecting the increased regulatory focus on particulates as a major contributor to health and environmental issues. 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. 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).

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 $300m^3$/min
- Qualitative monitoring and broken bag detection in stacks with air flow greater than $50m^3$/min
- No monitoring in stacks below $50m^3$/m

The division between the different types of monitoring on larger (Part A) processes (eg: chemical plants, steel mills, cement industry, utility boilers) regulated for integrated pollution by the Environment Agency is subject to more individual inspector discretion. Typically continuous measurement is required but for smaller emission points broken bag detection is sufficient. Very few industrial stacks have no continuous monitor.

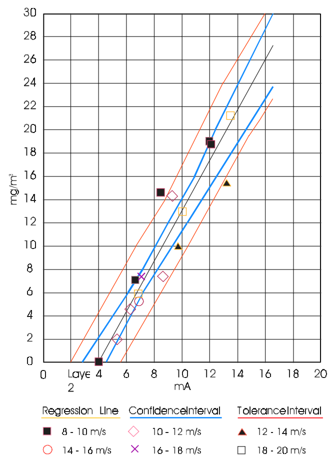
The UK Environment Agency has historically given little guidance to industrial operators on the quality of instrumentation required to satisfy continuous monitoring requirements. This has changed with the introduction of MCERTS, a new approval scheme for continuous emission monitors, adopted by the Environment Agency in the UK in 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.

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.
Specific 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.



Graph showing no velocity effect for DustAlert

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 particulates monitors:

- EPA will be requiring **Continuous Particulate Measurement or PM CEMS** (Particulate Matter Continuous Emission Monitors) in a number of industrial processes including Incinerator and Cement Kiln applications. A new standard PS-11 is being developed to define the performance of particulate monitors. This standard uses 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.
- 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.

3.2 Mass Emission and Velocity Monitoring

A new form of regulatory requirement for particulate measurement is continuous mass emission and flow measurement. There is a trend in most European countries to express particulate emission limits not just simply in terms of concentration (mg/m^3), but also in terms of mass flow emissions (eg g/hour). This reflects the environmental goal to minimise the total amount of pollution being emitted to atmosphere and that a large, high velocity stack has for the same mass concentration a higher environmental impact than a smaller lower velocity one. This change in regulator approach embodies the European IPPC (Integrated Pollution Prevention & Control) directive which places increased requirements on member states to maintain an emission inventory of total emissions. This again increases the need to measure mass emissions in addition to mass concentrations.

In processes with constant emission velocity, the mass flow is simply proportional to the emission concentration and may be calculated by the simple relationship with a fixed value of velocity:

$$M = C \times V \times A \times 3.6$$

Where: M = Mass Flow (g/hour)
C = Mass Concentration (mg/m^3)
V = Average Stack Velocity (m/s)
A = Stack Cross Sectional Area (m^2)

In emission sources with varying exit velocity the same equation may be used, however, there is the need to use the actual velocity on an ongoing basis to ensure a realistic measurement of mass flow. A choice of implementation exists between regular 'spot measurement and calculation' or continuous measurement. The recent trend is for concentration and velocity to be measured continuously, and then the mass flow can be calculated and reported on an up-to- date basis.

4 Use Of Dynamic Opacity (Scintillation) 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, Dynamic Opacity (Scintillation) and Electrodynamic are being used most commonly in new installations due to their regulatory acceptance and their suitability as pragmatic solutions to monitoring requirements. They are both now used extensively for continuous particulate concentration measurement in most parts of the industrial world including UK, Germany, Japan and Australia. They are also suitable for Mass Emission and Velocity measurement.

For reference, the other technologies used for particulate monitoring in certain applications are:

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

However, these are not considered further in this paper which concentrates on the use of Dynamic Opacity (Scintillation) and Electrodynamic technology in concentration and Mass Emission instruments. A description and overview of each technology follows:

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.

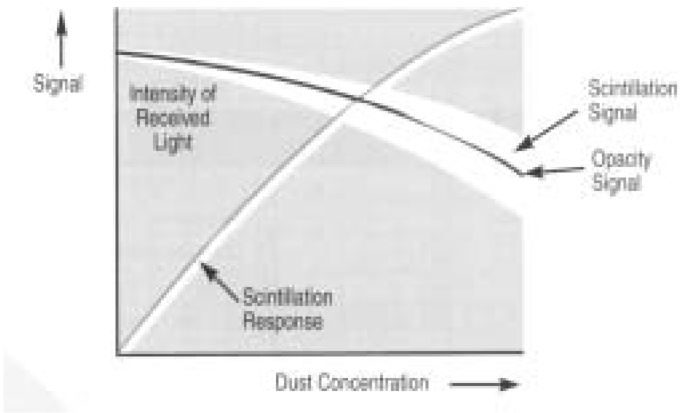


Diagram showing Dynamic Opacity vs concentration

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. Power generators and cement facilities in Queensland are among Australian users of these instruments.

Approvals

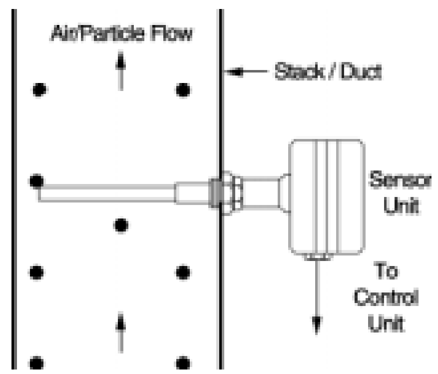
Dynamic Opacity (Scintillation) instruments are approved for regulatory use in both UK and Germany. The SC-600 manufactured by PCME holds an MCERTS approval for particulate measurement in the range of 0-150mg/m^3 . Processes for which it is approved include Electrostatic Precipitators and/or Coal Fire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

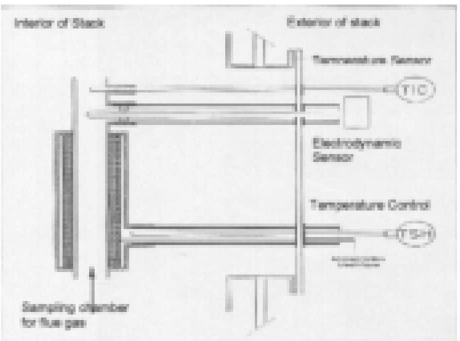
In applications where the particle charge, particle size and particle distribution remain constant the resulting alternating current is proportional to dust concentration. These instruments can be calibrated in mg/m^3 by comparison to the results of an isokinetic test.



Schematic of interaction between particle and electrodynamic sensor

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.
- The sensor can be incorporated in an in-situ heating chamber assembly to permit measurement in wet stacks. This is providing a pragmatic alternative to Beta systems.



Schematic of heated chamber and electrodynamic sensor for wet applications

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, Japan and Australia is widespread. Regulatory approvals exist for qualitative and measurement instruments in both the UK and Germany. They are used in many hundreds of applications in Australia often as a high end alternative to triboelectric.

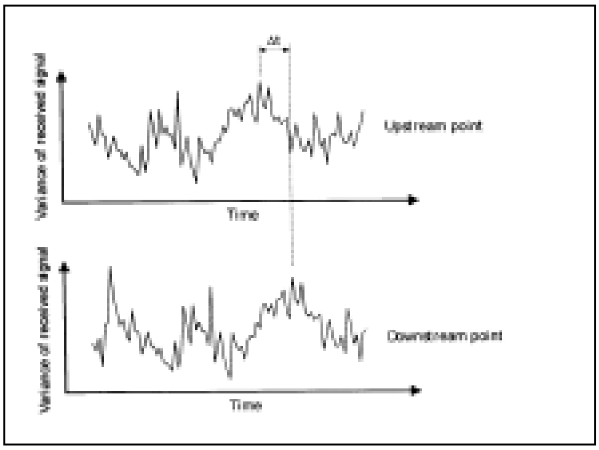
Approvals

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.

Accreditation			Product (s)
UK MCERTS	SIRA MC 990004/00 Category 4 (0-30mg/m^3)	Waste Incineration Baghouses	DT280/DT780
German TA-Luft/BlmSchV 27	936/807009/A (0-50mg/m^3 qualitative)	Filter Performance	DA60
German BlmSchV 13 & 17	936/807009/B (0-15mg/m^3)	Filter arrestment plant	270T/770T

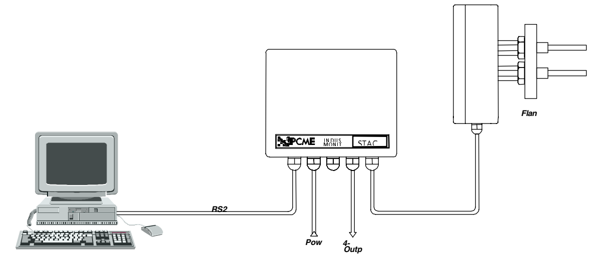
4.3 Electrodynamic And Scintillation Mass Emission And Velocity Instruments

Electrodynamic & Scintillation instruments can also be configured to measure stack velocity and hence mass emissions by using a second integrated sensor and a cross correlation technique. The principle of cross-correlation instruments is to derive the stack velocity from measuring the transit time of particles between two sensors mounted in the stack. Electrodynamic instruments work on the principle that particles carry a small amount of charge and, therefore, as the particles pass two rods they induce an electrical signature related to the charge distribution pattern. Provided the second sensor is not separated too far downstream from the first, the charge distribution pattern will be similar and a similar electrical signature will be induced on the second sensor. However, this pattern will be shifted in time in relation to the first pattern by the transit time of the particles. Scintillation velocity instruments use the dust signals derived from two optical heads for cross-correlation.



Graphs showing Signal produced at Upstream and Downstream Sensors

Cross-correlation is a signal processing procedure to determine the time lag between the two signals. The cross-correlation algorithm involves digitising the two signals to obtain the signal value at a number of different times. The complete correlation function is calculated by multiplying the signals against each other, but each time the signal is shifted by another increment. The peak of the correlation algorithm occurs for a total time increment equal to the time shift between the two signals.

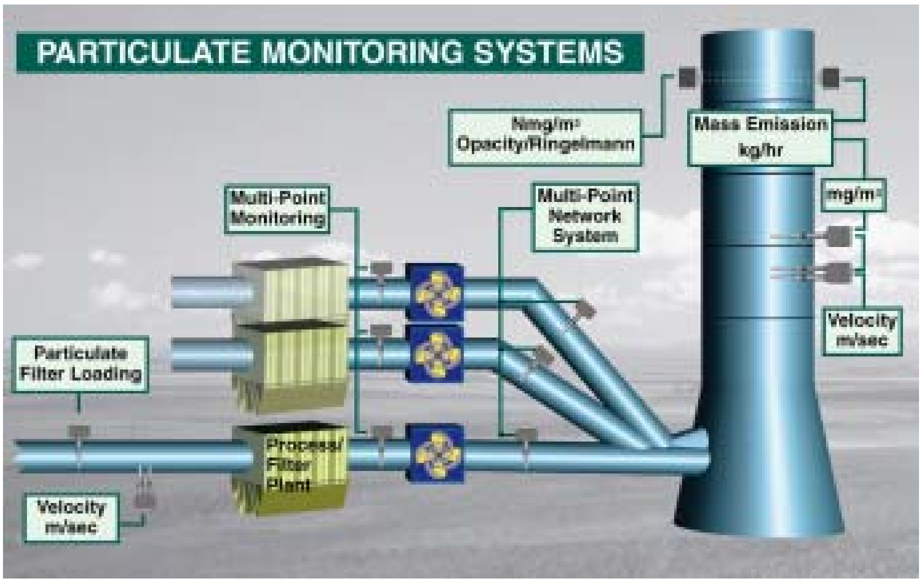


Schematic of Electrodynamic Mass Emission Sensor

Mass emission instruments use simultaneous velocity measurement from the cross- correlation technique and concentration measurement derived from the upstream sensor. This enables a single instrument to measure velocity, concentration and mass emission and provide a cost-effective solution to new regulatory requirements of concentration and mass emission measurement.

5 Instrument & Network Solutions

In the past instrument manufacturers such as PCME have tended to offer particulate measurement solutions as stand alone emission monitoring instruments, and indeed PCME has installed many thousands of Dynamic Opacity and Electrodynamic instruments on stacks. The need for stand alone CEMs (Continuous Emission Monitors) will continue due to benefits of redundancy, however networked systems will play a growing role in emissions monitoring on large plant. In a networked system multiple sensors are connected to a central control and data management system and this provides a cost effective and convenient method for measuring plant wide processes.



Multiple emission points to be monitored across an industrial site

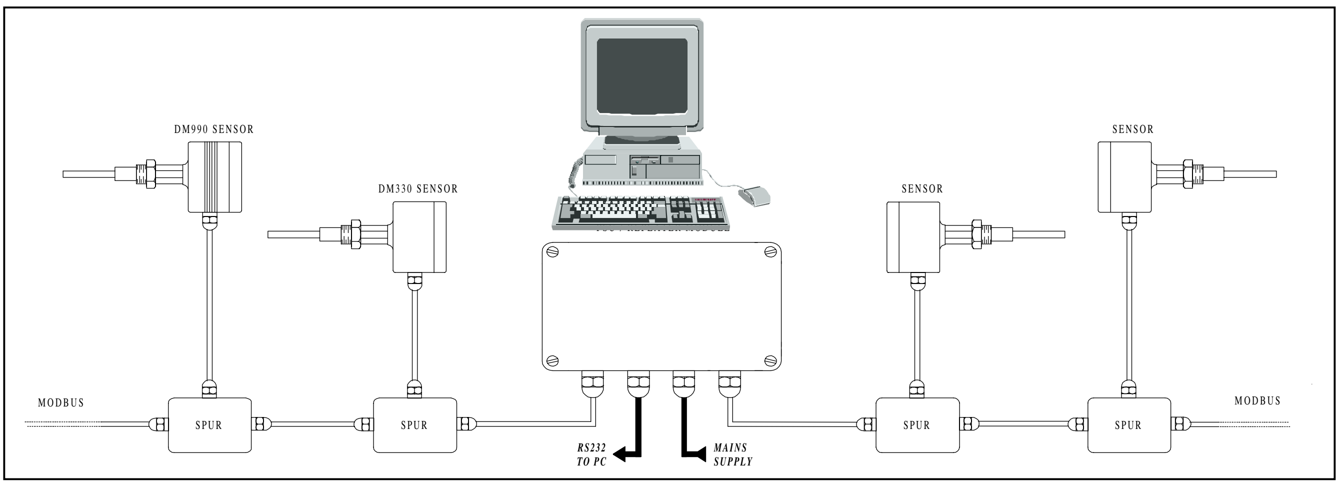
PCME now offers its Scintillation and Electrodynamic sensors not only in the form of individual CEM instruments, but also as part of network. A description follows for the network system.

5.1 Architecture

The sensors are connected by a single cable which both delivers power to the sensors and provides a MODBUS communication link between up to 255 sensors and a central Personal Computer or DCS (Digital Control System).

5.2 Sensors supported by the Network

The network can be connected to a variety of sensors so that the most appropriate sensor may be used for an application while still be networked with other sensors. For example a network in a cement plant would comprise Scintillation sensors on the stack from the Electrostatic Precipitators after the cement kiln and Electrodynamic sensors after the baghouse on coal and clinker mills. Sensors supported by the network include:

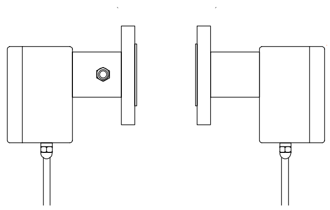


Architecture of Dustmaster network

SC-600 Sensor

This Dynamic Opacity (Scintillation) instrument, comprising transmitter and receiver mounted either side of the stack, is suitable for particle concentration monitoring in Electrostatic Precipitator, Combustion and large Bagfilter applications. This instrument has approvals which satisfy the MCERTS standard for continuous particulate monitors in the range of 0-150mg/m^3 and has automatic zero and span checks providing high quality control.

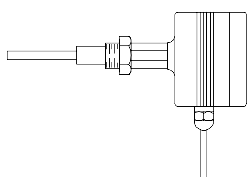
MEM-6000 Sensor



This instrument while similar to the SC-600, provides particulate velocity and mass emission in addition to particle concentration.

DM-990 Sensor

An Electrodynamic type sensor provides particulate concentration measurement in baghouses and is capable of measuring in applications with varying velocities, high humidities (non-condensing) and high temperatures (up to 600^{o}C). The sensor has automatic zero and span checks and automatic contamination failure detection.



DM-330 Sensor

A sensor suitable for particulate trend monitoring in baghouses with fixed velocities. Provides a signal proportional to dust levels.

MEM-7000 Sensor

An electrodynamic sensor suitable for measuring mass emissions and velocity in addition to concentration in drier, and bagfilter applications.

Auxiliary Input Module

An interface module which permits other particulate and non-dust sensors (ie from gas analysers on the same stack as the particulate monitor) to be connected to the network via 4-20mA or contact closure interface. This permits other approved sensors to be connected to the system.

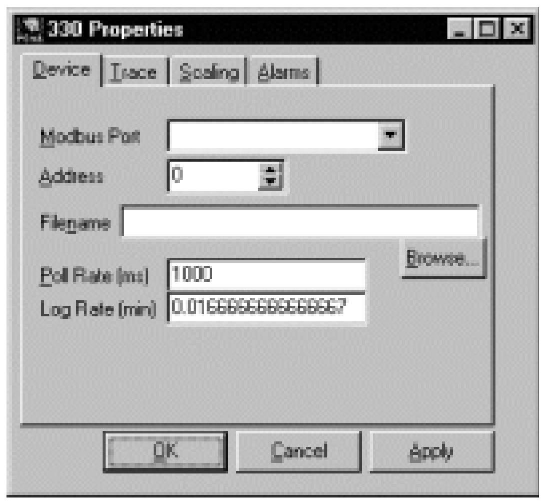
Broken Bag Locator Interface

A module to be connected to the baghouse cleaning controller to permit software to automatically identify location of breaking or failed bag rows.

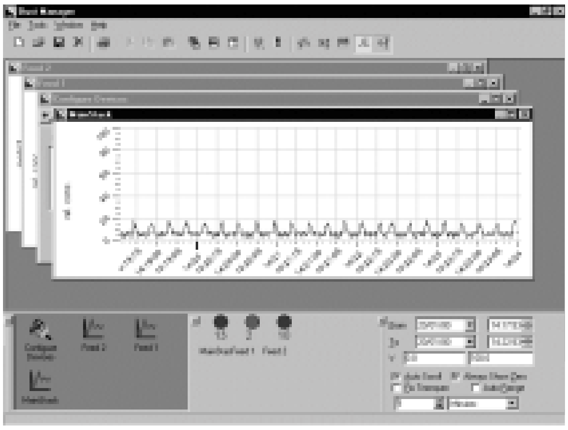
5.3 Operation of the System

The system is set up centrally from the PC or control unit. Parameters which are set as part of the initial configuration of a system are:

Numbers and types of sensors
Averaging periods for data analysis
Alarm and action levels
Data logging periods and data storage
External alarms and 4-20mA outputs
Sensor calibrations



The value of each process or emissions parameter may be tracked on the central PC along with the alarm status for each sensor on the network. An electronic alarm log (with record of actions taken to resolve incidents) is supported. Emission and process reports are produced directly from displayed and historically stored data .



6 CONCLUSION

Regulators around the world have taken a similar position in relation to monitoring particulate emission from industrial plant by requiring a combination of continuous concentration measurement and qualitative type monitoring. These requirements are being supplemented with new requirements for Mass Emission measurement on larger stacks. Dynamic Opacity (Scintillation) and Electrodynamic instruments have a proven track record of satisfying many of these requirements in measuring emissions from Electrostatic Precipitator and Bagfilter arrestment plant They are also certified for measurement in Germany and UK the only countries where approval schemes for particulate monitors exist. A new generation of particulate network has been developed permitting process operators to combine scintillation and electrodynamic sensors on the same monitoring network and provide an efficient solution to plant wide particulate emission monitoring.