LAND
AMETEK®

OPACITY AND PM MONITORING IN EMISSION STACKS

APPLICATION NOTE

INTRODUCTION

Smoke and dust emissions from industrial plants, such as coal-fired power stations and industrial incinerators, damage the environment and pose a health hazard to humans.

Subsequently these emissions are regulated by government agencies across the world. These include the Environmental Protection Agencies (EPA) in the USA and the UK. Globally, government agencies recognise the need for clean air and respond to the demands from the population for a healthier environment.

Smoke and dust particles emitted from industrial stacks are a major source of air pollution, and the effects of small particles on human health are a major source of respiratory disorders. Therefore, minimising the emissions from industrial stacks remains a goal, driving ever greater reductions in emissions.

Typically, an industrial emission source must comply to an Emission Limit Value (ELV), which denotes the maximum mass emission over time it may emit without incurring penalties.

Traditionally, particulate matter (PM) emissions are measured optically by a transmissometer (opacity monitor) which measures the amount of light crossing the stack without being lost by scattering, reflection or absorption by the particles. This technique works well for moderate and high concentrations of dust.

Where emissions are low, an alternative technique, employing light scattering or charge transfer, offers higher sensitivity.

In some cases, opacity is used as a process control parameter and opacity monitors are ideal as they do not need to meet all the regulatory requirements. Such non-compliance opacity monitors are perfect to monitor the smoke emissions in a duct which does not emit directly to the ambient air, possibly because the flue gases have to undergo subsequent clean-up.

OPACITY, PM AND LIGHT SCATTERING

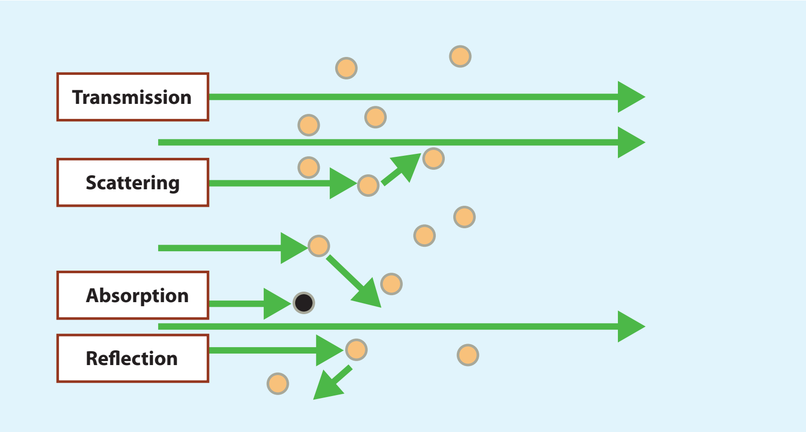

Figure 1: Loss through scattering, absorption and reflection

Opacity is defined under the ASTM D6216 standard as the degree to which PM emissions reduce the intensity of transmitted photopic light (due to absorption, reflection and scattering) and obscure the view of an object through ambient air, an effluent gas stream, or an optical medium, of a given pathlength.

These processes are illustrated in Figure 1, which shows some of the light rays passing through the sample, while others are scattered, absorbed or reflected.

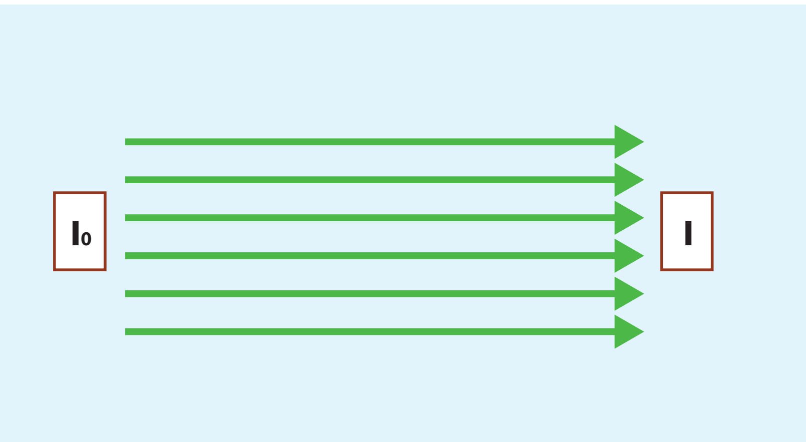

Figure 2: Sample with 0% opacity

If the intensity of light entering the sample is represented by I_0 and the intensity leaving the sample is I, we can express this mathematically as:

Opacity = (1 - I/I_0) x 100%

If the sample contains no particles, the intensities I and I_0 will be the same, so the opacity is 0%.

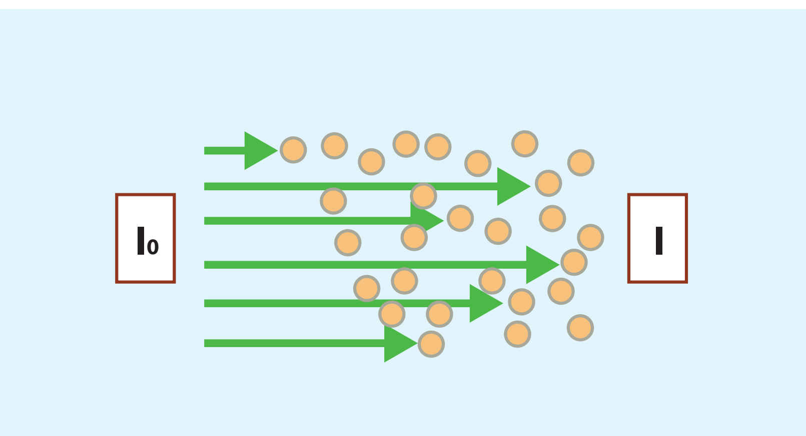

Figure 3: Sample with 100% opacity

If the sample has so many particles that none of the light passes all the way through, then I = 0, and the opacity is 100%.

REGULATORY COMPLIANCE: OPACITY AND PM CONCENTRATION

Some regulatory bodies set the ELV in terms of the plume opacity at the stack exit. In these cases, the ELV will typically be 10% or 20% opacity, and the plant operator will be fined if emissions are above this level.

In other cases, the ELV will refer to the mass concentration of PM emitted from the stack, and the ELV will be expressed as a mass concentration in the form 10 mg/m^3 or 50 mg/m^3.

The US EPA has traditionally set emission limits as percentage opacity, but more recent rules have shifted to mass concentration units. European regulators have always set limits in mass concentration limits.

In many cases, the choice of measurement units is laid down in the relevant regulations. However, some US EPA rules, such as the MATS rule, give users a choice of using an opacity monitor or a PM-CEMS, with different quality-control requirements depending on the measurement type.

Although there is a close relationship between the two measurements, there are practical differences between the ways they are measured.

An opacity monitor measures the amount of light lost through absorption and scattering, and converts it to a meaningful number, the stack opacity. This number is shown on the display and made available as an output in % opacity.

A PM monitor also measures an optical characteristic of the stack gas – such as the opacity or the intensity of scattered light – but it then takes this value and uses it to calculate the PM concentration in mg/m^3. The calculation uses an experimentally-determined calibration factor unique to that specific installation. An isokinetic sample is the standard reference method used to determine the actual mass concentration in a flue stack over a given time period and given set of stack conditions. This value is then used to set an instrument calibration factor for a PM monitor in order for it to subsequently measure a mass concentration, typically in mg/m^3.

NON-COMPLIANCE OPACITY

There are many applications where opacity measurement is needed for purposes other than regulatory compliance, including combustion optimization and process control. In such cases, a simpler design such as the AMETEK Land 4400 opacity monitor can be used.

PRACTICAL STACK GAS OPACITY MEASUREMENT

Compliance opacity monitors must operate reliably and continuously, 24 hours a day, for many years. Usually, they are mounted in an elevated, outdoor location where they may be exposed to extremes of temperature, heavy rain and strong winds.

Although they are solid structures, stacks and ducts move depending on process conditions, so it is important that the monitor design accommodates these movements.

Most modern opacity monitors, including the AMETEK Land 4500 MkIII, use a double-pass design. This uses a transceiver to project a beam of light across the stack, hitting a reflector which returns the light to a detector mounted in the receiver.

This is shown schematically in Figure 4.

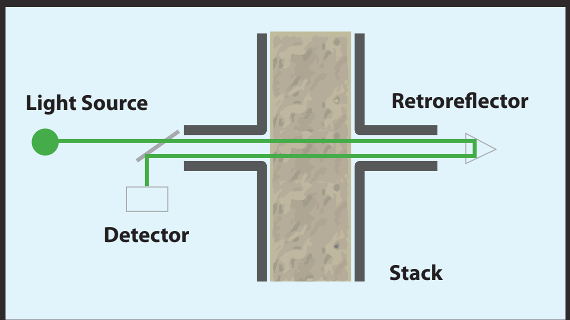

Figure 4: Schematic of a double-pass opacity monitor

There are a number of advantages to the double-pass design which makes it the preferred choice.

These include:

- The low-level sensitivity is increased because the light passes through the stack gases twice
- The reflector is a passive optical device, so requires no power
- A simulated zero condition can be achieved by placing a reflector in the beam at the transceiver, effectively short-circuiting the stack

AMETEK LAND 4500 MkIII

COMPONENTS OF A PRACTICAL OPACITY MONITORING SYSTEM

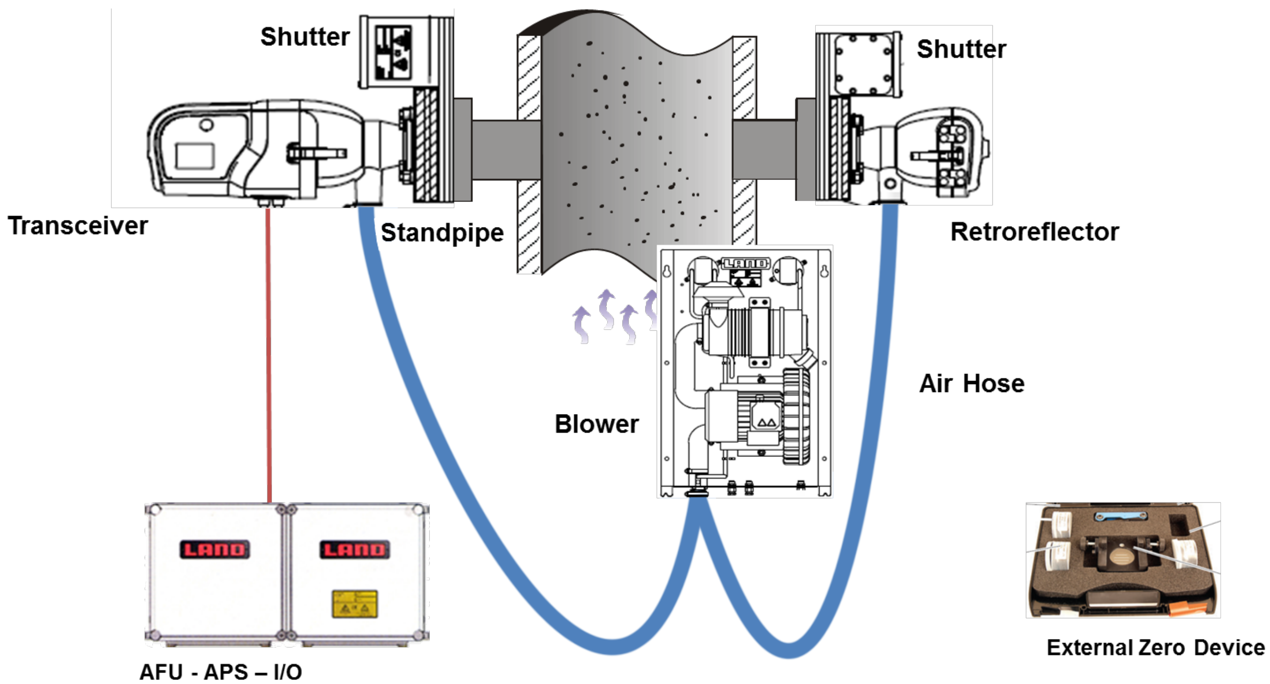

Figure 5: Components of the AMETEK Land Model 4500 MkIII

Typically Opacity Monitors consist of a transmissiometer and associated equipment that provides reliable operation, easy installation and calibration. The AMETEK Land Model 4500 MkIII incorporates all these elements as shown in Figure 5

The principal components are:

Transceiver: The heart of the system, containing the light source and detectors, user interface and main microprocessor.

Retroreflector: A passive reflector, the retroreflector differs from a mirror because it returns the light towards the source, regardless of the angle of incidence. This makes it much less sensitive to changes in alignment which may occur as the stack temperature changes.

Standpipes: These mount the transceiver and retro to the stack, and also allow for adjustment of the instrument's optical alignment.

Purge blower: Continuous air purge is used to protect the instrument's delicate optical surfaces from hot, corrosive stack gases.

Air hose: This connects the purge blower to the transceiver and retroreflector.

Fail-safe shutters: These close automatically to provide protection to the optics if the purge fails temporarily. They also protect the instrument and operator during servicing on positive-pressure ducts, where the stack gases would otherwise escape when the instrument is removed from the stack for calibration and servicing.

AFU-APS-I/O: The transceiver requires 24 V DC power and provides limited connectivity. The Auxiliary Function Unit (AFU), Auxiliary Power Supply (APS) and I/O module provide additional functions including two 4-20 mA signals, mains power input and convenient screw-terminal connections which avoid the need for a customer-provided junction box.

External zero device: This simulates a clear-path condition for servicing and routine calibration checks. It is required for all applications subject to US EPA regulations.

Each opacity monitor has to be configured and calibrated for the specific installation where it will be used.

PM MEASUREMENT

An opacity monitor can be used to measure moderate to high concentrations of PM, but the lowest practical range is generally between 0-20 mg/m^3, depending on the pathlength.

The ELV for many applications is now set lower than this, which may require an alternative measurement technique.

Table 1 shows the ELV for electricity generating units (EGUs) under the latest US EPA regulations.

Table 2 shows the ELV for EGUs under the EU Industrial Emissions Directive (IED). Many of the ELVs are too low to allow the use of an opacity monitor. Users in the US are, in many cases, usually reluctant to use opacity monitors to measure PM, as this could require them to comply with both opacity and PM limits, which in turn imposes additional record-keeping and reporting burdens.

As can be seen, some of the ELVs above would be difficult to measure using an opacity monitor, unless the path length was enough to achieve the sensitivity required. However, many countries still apply opacity as their de facto measuring technique for large combustion plants, as it may respond more appropriately to the combustion characteristics found with higher emissions especially when using coal.

To measure PM in a continuous emissions monitoring system (PM-CEMS), a range of measurement techniques are available.

Type of EGU	New	Existing
Coal-fired	9E-2 lb/MWh ≈14 mg/m^3	3E-2 lb/MMBtu ≈53 mg/m^3
New IGCC	7E-2 lb/MWh ≈11 mg/m^3	4E-2 lb/MMBtu ≈70 mg/m^3
Oil-fired (continental)	3E-1 lb/MWh ≈50 mg/m^3	3E-2 lb/MMBtu ≈56 mg/m^3
Oil-fired (non-continental)	3E-1 lb/MWh ≈50 mg/m^3	3E-2 lb/MMBtu ≈56 mg/m^3
Solid oil-derived	3E-2 lb/MWh ≈5 mg/m^3	8E-3 lb/MMBtu ≈14 mg/m^3

Table 1: Emission limits under the EPA MATS rule

	Type of EGU		
MW	**Solid fuel**	**Biomass**	**Liquid**
50-100	30	30	30
100-300	25	20	25
>300	20	20	20

Table 2: EU requirements under IED – shows ELVs for large combustion plants

LASER BACK-SCATTERING

In this process, a laser shines into the flue and a lens collects the back-scattered light which is focused onto a detector. The scattered light intensity can be correlated with the dust concentration.

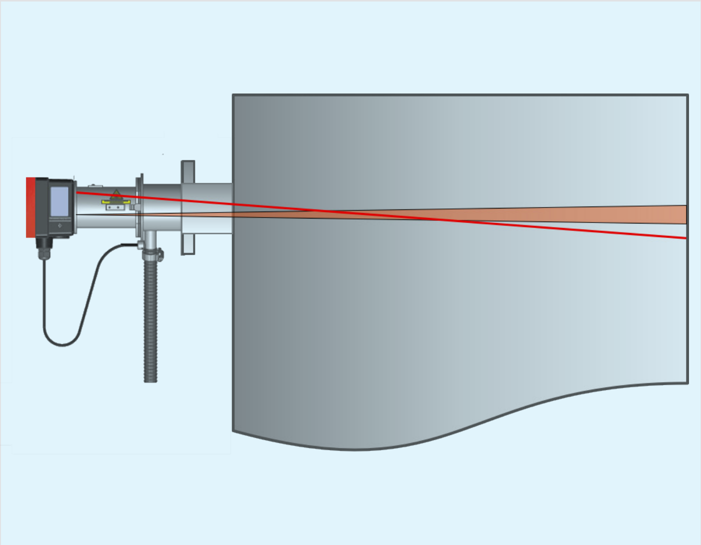

Figure 6: Laser back-scattering

This is an attractively simple technique and, unlike an opacity monitor, only needs to be installed on one side of the stack.

However, it has a number of limitations:

- The measurement can be made quite close to the stack wall, so it may not be a truly representative measurement
- The back-scattered signal can be quite weak, so it is less sensitive than a forward-scatter monitor
- The signal is sensitive to changes in the particle size distribution
- Laser light reflected from the far wall of the stack can give a spurious measurement – a problem in small ducts.
- The system cannot distinguish water drops from dust particles, so it cannot be used in processes where condensed water could be present. This means that it is not suitable for installation after a wet flue gas desulphurisation (FGD) system (however, this is also the case for most other in-situ measuring techniques which do not compensate for water droplets in the flue gas)
- AMETEK Land 4750-PM employs the forward-scattering technique

LASER FORWARD-SCATTERING

With this arrangement, a probe is inserted into the stack. A laser shines down the probe and into a measurement region. A lens or mirror at the end of the probe collects the light, which is scattered a few degrees off-axis, and returns it to a detector in the probe head.

Like the other systems, this requires access to just one side of the stack. Low-angle forward-scattering also provides the strongest signal, so it gives the best sensitivity for low-level measurements.

In addition, changes in particle size have a smaller effect on this technique compared to back-scatter or side-scatter configurations, as they tend to use the MIE scattering principle, which is more sensitive to smaller particles found after more modern dust arrestment plant.

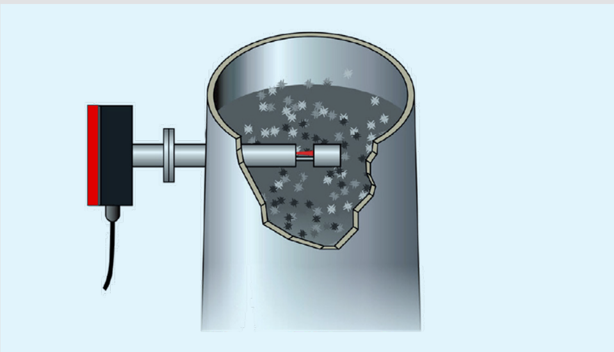

Figure 8: Laser forward-scattering installation

Some points to note:

- The probe is inserted into the stack, so the flue temperature is limited to between 400 and 500 °C (752 and 932 °F) depending on the design and materials selected
- As with the other in-situ techniques, the measurement is affected by condensed water drops

The AMETEK Land 4650-PM employs the laser forward-scattering technique.

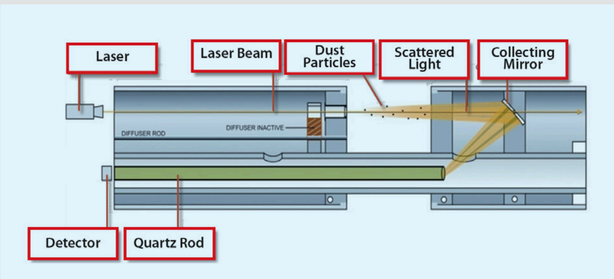

Figure 9: Laser forward-scattering measurement detail

EXTRACTIVE SYSTEMS

The only method of eliminating interference from condensed water drops is to extract the sample from the stack, heat it to evaporate any water present, and then measure the dust concentration.

Two methods are generally accepted:

- Using a laser forward-scattering sensor similar to the in-situ probe
- Beta ray attenuation

For beta ray attenuation, the sample flows through a paper tape filter for several minutes. The exposed filter is then placed between a source of beta rays and a Geiger-Muller tube. The amount of beta radiation absorbed is proportional to the mass of the filter plus any PM deposited.

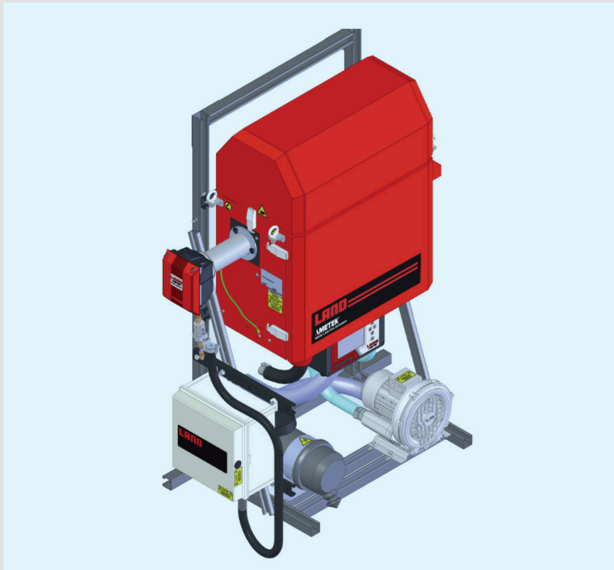

Figure 10: Extractive PM analyser

This type of analyser allows measurements in gas streams where condensed water drops are present. However, they are complex and expensive, costing significantly more than an in-situ instrument, and the sample system greatly increases maintenance requirements. For these reasons, they are generally not used in applications where an alternative approach will work.

TRIBOELECTRIC (ELECTRODYNAMIC) PROBE

The inherent sensitivity of charge transfer devices allow them to be used where dust concentrations are very low (typicallyafter bag filters) and can also provide a good indicator of a bag filter's performance.
Some more advanced charge transfer systems can be used as a PM-CEMS and can be quantified to measure dust concentration complying to environmental regulatory requirements.

A baghouse is a highly efficient method for removing PM from flue gases as long as all of the bags remain in good condition. However, as the bags age they begin to leak and allow increasing amounts of PM to pass through. A Bag Leak Detector (BLD) is used to determine whether a bag is beginning to deteriorate.

European regulatory requirements call for filter leak and filter dust monitors to be fitted where emissions are very low after bag filters in secondary non-combustion processes under EN15859. This function requires a very sensitive measurement, and therefore, traditionally, transmissometers do not function well in these applications.

AMETEK LAND 4650-PM

The 4650-PM is a PM monitor which uses the laser forward-scattering technique, and is ideally suited to measure dust in the cleanest modern industrial processes.

Depending on the regulatory requirements, it can be used as either a PM-CEMS or a continuous parametric monitoring system (PM-CPMS).

Like all forward-scattering instruments, it has very high sensitivity, while its response shows minimal dependence on particle size, and the measurement region is sufficiently far from the stack wall to give a representative sample.

However, the 4650-PM also has a number of features that distinguish it from competing products:

- The scattered light is collected by a large-area mirror which enhances the signal-to-noise ratio and provides a very low detection limit
- There are no moving parts in the measurement optics, so the stability is excellent
- The span check is performed by moving a scattering element into the laser beam and detecting the amount of scattered light. This patented technique provides a true validation of the measurement method. Competing products simulate an upscale calibration check by moving the detection optics directly into the laser beam and measuring the transmitted light intensity, which reduces the mechanical stability of the optical system
- The 4650-PM uses a large-area rigid quartz rod to transmit the scattered light to the detector. Competing designs which employ moving parts must use an optical fibre – repeated flexing of the fibre leads to its degradation and ultimate failure

In addition to automatic calibration checks, the 4650-PM allows for periodic manual audits, which confirm its long-term stability relative to external audit devices.

In most cases, the audit requires the probe to be removed from the stack and allowed to cool. Once it is at ambient temperature, three calibrated audit devices are inserted sequentially into the measurement position, as shown in Figure 13.

Figure 11: 4650-PM probe and control unit

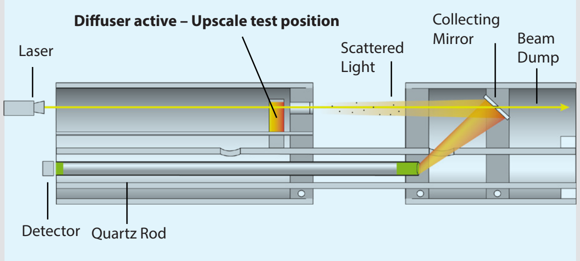

Figure 12: 4650-PM upscale cal check device active with diffuser in the test position

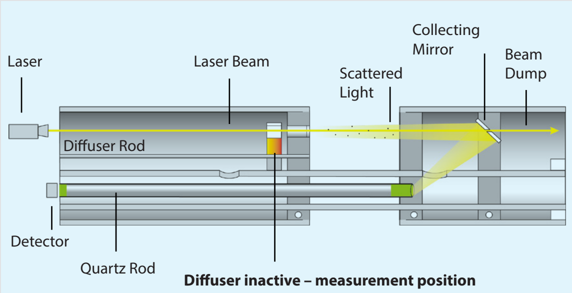

Figure 13: 4650-PM upscale cal check device inactive

CORRELATION TESTING

Nearly all PM-CEMS, including opacity and light-scattering devices, use inferential methods which measure a quantity related to dust density. In order to determine the actual PM concentration, they need to be calibrated for the specific installation conditions by correlating the monitor output with the result of a standard reference method.

The details of the standard reference methods may differ, but all are based on measurements of a dust sample, collected isokinetically by a skilled stack tester or test team.

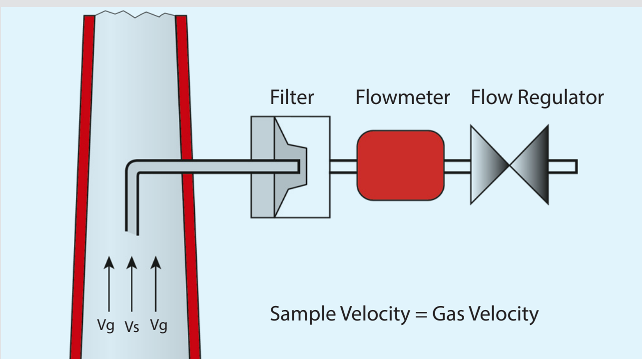

Figure 14: Schematic of a reference method sample system

A stainless steel probe is inserted into the stack, then the sample flow is adjusted so that the velocity of the sample entering the probe matches that of the stack gases. This is called isokinetic sampling, and ensures that the dust sample entering the probe is representative of the dust load in the stack.

As the dust particles have much more momentum than the gas molecules, they tend to continue to travel in a straight line, even if the streamlines of the gas flow are diverted, resulting in sampling errors.

In an isokinetic flow pattern, the stack velocity (W) is equal to the sample velocity (V) so the streamlines remain straight. If W > V, then the probe will tend to over-sample the dust particles, while if W < V, then the heavier dust particles will tend to miss the sample nozzle, so the dust concentration will be under-sampled.

If W > V, then the probe will tend to over-sample the dust particles, while if W < V, then the heavier dust particles will tend to miss the sample nozzle, so the dust concentration will be over-sampled.

Once the sample has been collected by the probe, it passes through a filter which collects the dust particles. This filter is weighed before and after sampling, so the difference is equal to the mass of dust collected.

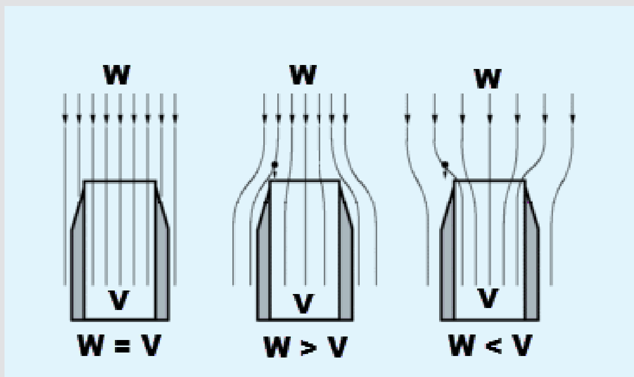

Figure 15: Isokinetic and non-isokinetic flow patterns

After drying, the gas sample passes through a gas meter which measures its total volume. By comparing the dust mass to the gas volume, the dust density measurement in the stack can be obtained in mg/m^3. The measurement protocols for isokinetic sampling are EPA Method 5 and EN 13284:1.

An isokinetic sample train is a complicated device and requires care and experience to obtain an accurate measurement – the measurement uncertainty is typically between 5 and 20% of the measured value.

Low dust concentrations are especially difficult to measure, and it may take several hours to build up a measurable amount of dust on the filter. Even then, the uncertainty in the methods can lead to negative values for dust concentrations. Paper filters are particularly problematic, as they may lose fibres from their surface, affecting weight measurements.

A series of measurements is taken under different process operating conditions, and the resulting analyser output plotted against the simultaneously measured reference method data. Both PS-11 (the US performance standard for continuous PM monitors) and EN 13284:2 (the EU calibration methodology for continuous PM monitors) require a minimum of 15 valid data points, though the criteria for rejecting invalid data differ between the two methods.

The result is a correlation graph which is valid for that specific analyser at that specific location, burning that specific fuel. It is generally acceptable to switch fuel sources – e.g. between different coals – but switching from coal to oil, or vice versa, will invalidate the correlation results. Figure 16 shows an example of a correlation graph.

Obtaining the required range of operating conditions is one of the biggest challenges in performing a correlation test.

Once the correlation graph has been plotted, statistical tests are applied to assess how well the data fits the correlation curve. Assuming this data passes the test, the correlation curve is programmed into the gas analyser and the system can be used to make valid measurements of dust concentration for compliance purposes.

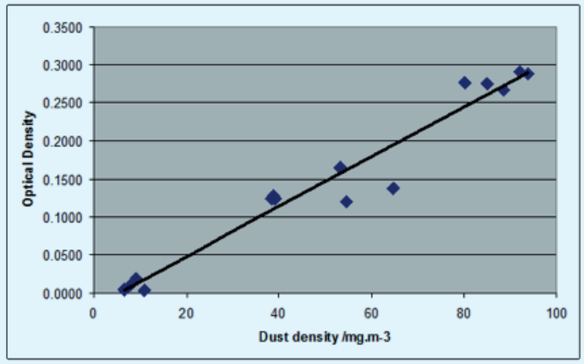

Figure 16: Correlation graph showing low, mid and high-level PM concentrations

WHAT IS A PM-CPMS?

Correlation tests can involve considerable costs, so in some cases regulations allow a simpler procedure to be used to demonstrate that a facility is meeting its environmental protection obligations.

A PM-CPMS uses three reference measurements to set an operating limit for the process. The procedure differs depending upon the detail of the regulations. For example, the regulations for electricity generating units under the Mercury and Air Toxic Standards rule can be summarised as follows:

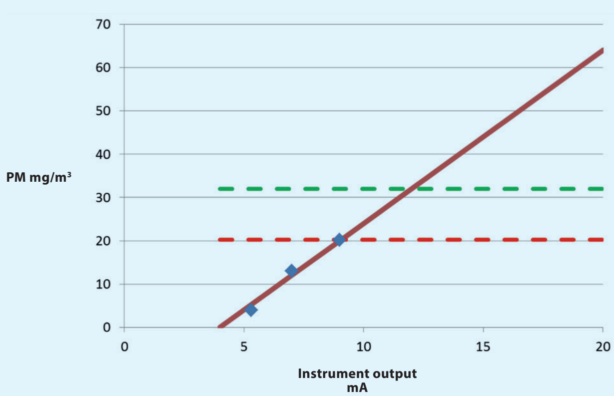

Figure 17: Graph showing operating limit (red) and ELV (green) for a PM-CPMS installed on a power plant

- Install a PM monitor based on approved technology such as light scattering or beta ray absorption. The output may be in units of mA, light scattering intensity or other raw data values, and the instrument must have a detection limit better than 0.5 mg/m^3

- If the stack tests show the emissions are below the required emission limit value, the operating limit is the highest of the nine hourly-averaged values of the PM-CEMS during the test

- Perform three stack tests using a standard reference method, with each test lasting three hours. During this period, record nine hourly averages of the PM-CPMS output

- The 30-day rolling average of the PM-CPMS output may not exceed the operating limit. The operating limit is, therefore, somewhat less than the emission limit value. In this way, the site operator benefits from a simpler test regime, but the trade-off is reduced operational flexibility.

AMETEK LAND SOLUTION

Our in-house service centres provide after-sales services to ensure you get the best performance from your system. This includes technical support, certification, calibration, commissioning, repairs, servicing, preventative maintenance and training. Our highly trained technicians can also attend your site to cover planned maintenance schedules and repair emergency breakdowns.

4400

A Dust and opacity monitor for monitoring combustion processes where automatic calibration checks are not needed.

COMBUSTION & EMISSION MONITORING

4500MkIII

A high-specification opacity and dust monitor meeting US and European standards for monitoring combustion processes.

COMBUSTION & EMISSION MONITORING

4650-PM

High-sensitivity, forward-scatter laser measurement for particulate matter, for use in combustion processes where condensed water is not present.

COMBUSTION & EMISSION MONITORING

4750 PM

A back-scatter laser PM analyser designed for use as a continuous emissions monitor for compliance or process monitoring.

COMBUSTION & EMISSION MONITORING

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