Techniques to measure particulate matter emissions from stationary sources: A critical technology review using Multi Criteria Decision Analysis (MCDA)

Daniel Nicklin[1] and Hamidreza Gohari Darabkhani[2]*

[1, 2] Department of Design and Engineering, School of Creative Arts and Engineering, Staffordshire University, Stoke-on-Trent, ST4 2DE, United Kingdom

*Corresponding Author email: h.g.darabkhani@staffs.ac.uk

Abstract

This review article presents an overview of the commercially available methods to measure particulate matter (PM) from stationary sources, focusing on techniques to measure mass concentration. Mass concentration is the requirement for the majority of current regulations not only in the UK and Europe but also Worldwide. The process of particulate emission monitoring has been used and developed over the last 30 years as a result of increasing demands of legislation development and clean air initiatives. When deciding upon the measurement technique, the operator must consider; range of device, portability, usability, installation requirements, expected concentration, purpose of measurement, particle characteristics, cost and diameter of stack. This review aims to; give direction to operators looking for a measurement technique to measure mass concentration of particulate matter emissions, give direction to researchers working within the field of particulate measurement with a view to improving existing and developing new techniques and give strategy for selection of equipment. A literature review, industrial survey and Multi Criteria Decision Analysis (MCDA) were used for comprehensive analysis of nine measurement techniques operating in a full range of applications, highlighting the importance of matching a suitable device with the intended application. There is currently no suitable method available to measure mass both directly and continuously, resulting in using either the Standard Reference Method (SRM) or a continuous particulate monitor which requires calibration to its application using the SRM to obtain meaningful results. There is currently no single continuous particulate monitor available suitable for all applications.

Keywords

Particulate matter; emissions monitoring; stack emissions; stationary sources; mass concentration; air pollution.

Abbreviations

Multi Criteria Decision Analysis: (MCDA)

Standard Reference Method (SRM)

Tapered Element Oscillating Microbalance (TEOM)

Preference Ranking Organisation Method for Enrichment Evaluation (PROMETHEE)

Monitoring Certification Scheme (MCERTS)

Particulate and Compliance Emission Monitoring (PCME)

Ratiometric opacity – (RO)

Standard opacity – (SO)

Back scatter laser – (BSL)

Forward scatter laser – (FSL)

Beta attenuation – (BA)

Triboelectric probe – (TP)

Electrodynamic probe – (EP)

1 Introduction

Maintaining a good level of air quality is one of the foremost environmental problems facing our society today. The current discharge of large amounts of particulate matter into the atmosphere poses a threat to quality of life (Corrigan et al., 2018), raises various public health issues, and requires urgent attention (Favez et al., 2007). Particulate matter affects more people than any other pollutant (World Health Organization, 2015), negatively impacting health (Djoumi et al., 2016; Kamiya et al., 2011; Koehler and Peters, 2015). Particulate matter is known to be associated with adverse effects on the health of humans particularly affecting those suffering with any kind of respiratory diseases (Time et al., 2018). Cardiovascular and respiratory diseases have been linked to the exposure of particulate matter with high exposure to particulate increasing the risk of lung cancer (Environment Agency, 2012; Pope et al., 2020; Sanju Thomas, Farah H. Villa-López, Jan Theunis, Jan Peters, Marina Cole, 2015; World Health Organization, 2015). According to the United Kingdom Environmental Agency (Environment Agency, 2017a) it is the fine particles formed by combustion that are the main cause of the harmful effects (Brodny and Tutak, 2019).

The Environmental Agency describe the various sources of particulate as the combustion of coal, oil, petrol/diesel, wood and biomass. They are made up of sulphates, nitrates, hydrogen ions, ammonium, elemental carbon, silica, alumina organic compounds, trace elements, trace metals and particle bound water (Environment Agency, 2012). Particulate emissions in flue gasses are produced by combustion of fuel or waste, whilst the characteristics and quantity of the particulate depends upon the type of fuel and the design of the process.

Requirements for installing and operating a particulate mass concentration measurement device can vary, including, ensuring compliance with legislation and to optimise, monitor or control combustion processes. The application will influence the approach to monitoring stack emissions, which includes both periodic measurements and/or continuous emissions monitoring. Periodic measurements usually have a representative sample taken from the stack to a laboratory for analysis. Continuous monitoring has automatic measurements carried out either in the stack or on a sample automatically taken from the stack and analysed. Continuous methods require calibration against the standard reference method (Green and Fuller, 2006; Soysal et al., 2017).

The performance and suitability of any particulate monitor is application dependent and the fundamental issue with obtaining good results is to ensure that the instrument is fit for the intended purpose. Meyer (Meyer, 2004) states that difficulties surrounding accurate particulate capture include: particulate being the only air pollutant not defined by its molecular composition, particulate containing water droplets can give misleading results, and some particulate can volatise at ambient temperature.

This paper reviews 9 measurement techniques detailed in Figure 1 and Table 1 in a full application-based analysis through a literature review, industrial survey and Multi Criteria Decision Analysis (MCDA). These techniques are commercially available and currently in use for particulate measurement in combustion processes.

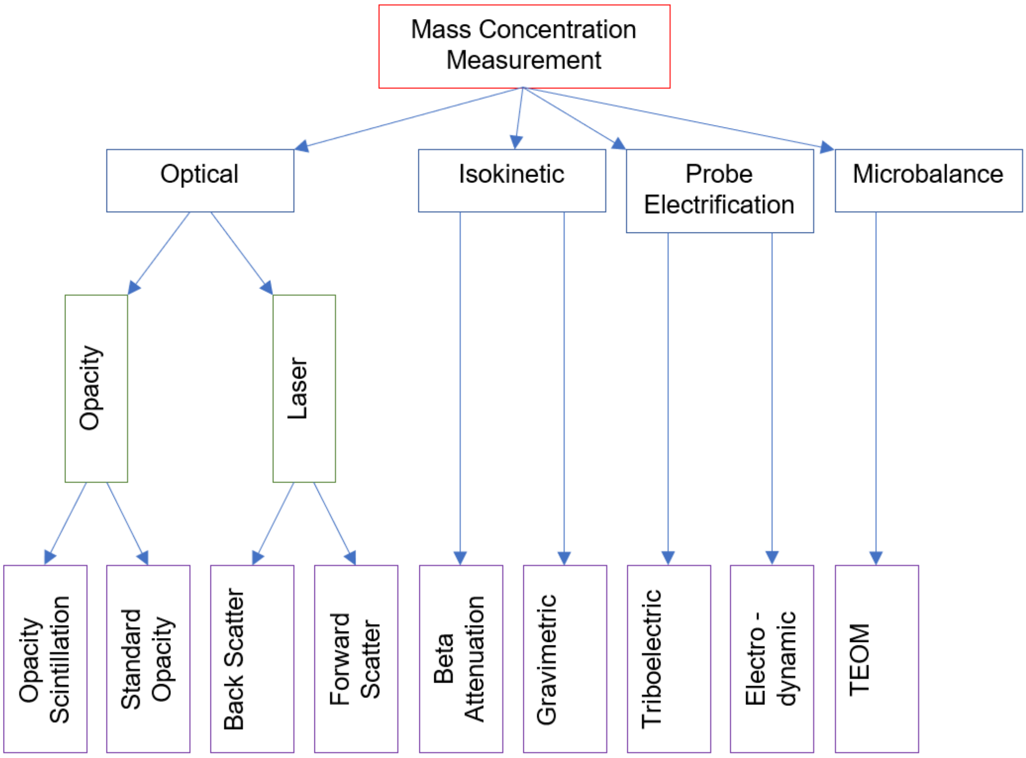

Figure 1 Mass Concentration Measurement Techniques

2 Research Methodology

This review paper used three techniques to complete a full analysis of techniques to measure particulate matter emissions from stationary sources including;

- Literature review
- Industrial survey
- MCDA

This section will give an overview the research methodology used through this project, further detail is also given in the relevant section of this report.

2.1 Literature Review

A comprehensive literature review was undertaken to give the reader an understanding of the commercially available techniques to measure particulate matter from combustion processes.

The literature review was conducted in stages by searching carefully considered key terms including;

- all available measurement techniques, ‘opacity scintillation’, ‘standard opacity’, ‘back scatter’, ‘forward scatter’, ‘beta attenuation’, ‘gravimetric’, ‘triboelectric’, ‘electrodynamic’ and ‘tapered element oscillating microbalance (TEOM)’
- categories for particulate measurement, ‘continuous and periodic particulate measurement’, ‘in-situ and extractive measurement’, ‘in-stack and out-stack sampling’ and ‘direct and indirect particulate measurement’
- ‘dust particulate formation from stationary sources’
- legislation for particulate measurement, ‘stationary source emissions legislation’, ‘dust particulate measurement legislation’, ‘emissions legislation’ and ‘emissions directive’
- ‘multi criteria decision analysis’ and ‘preference ranking organisation method for enrichment evaluation (PROMETHEE)’

The literature review seeks to give an overview of the current state of the commercially available measurement techniques for dust particulate measurement to help researchers and operators of plant to choose the most suitable equipment for their application and to develop and check criteria against survey results for multi criteria decision analysis weighting.

2.2 Industrial Survey

An industrial survey was undertaken as a systematic method of calculating the weighting for each criteria to be assessed in the MCDA as well as gaining information on the current state of the industry with a view to providing suggestions for improvement for further research.

Ostovare (Ostovare and Shahraki, 2019) successfully used a survey of an expert team to develop criteria and weight for use with the PROMETHEE MCDA methodology. This project seeks to successfully implement a similar model, using a carefully designed industrial survey and the PROMETHEE method to successfully determine the best approach to dust particulate measurement from stationary sources.

2.3 Multi Criteria Decision Analysis

The decision process of selecting the most suitable dust particulate monitor is complex due to its multivariate nature, with poor decisions having costly implications. It is not acceptable to select a device simply because it is a suitable match to one of the many criteria, therefore a more detailed approach should be taken and one which this review paper details.

MCDA is a formal approach whose purpose is to aid a decision-making process by fostering in decision makers the development of a structured thinking about the decision problem at hand (Keller et al., 1991).

In this project, for the purposes of the MCDA, a survey and literature review were used to derive;

- criteria for each evaluation (measurement technology) to be analysed against
- weighting for each evaluation
- application based criteria to analyse the use of the available measurement technologies in a range of applications
- appropriate methodology for MCDA framework

The PROMETHEE method of decision analysis was chosen for this project. The method is well adapted to a problem where a finite number of alternative actions are to be ranked considering several criteria (Machrafi, 2012) and is suited to smaller data sets

(Gunawardena et al., 2013). Ishizaka (Ishizaka and Nemery, 2011) completed a study to select the best statistical distribution and introduced the use of PROMETHEE method stating that it allows for the preferences of the decision maker to be fully considered rather than imposing a set of parameters. In this project the preferences of the decision maker (researcher or plant operator) are to be fully considered as there can be significant cost and operational implications caused by poor selection of equipment.

3 Categories for Measurement Techniques

Particulate measuring devices designed for use on stationary sources can be categorised into the following groups depending upon their operating characteristics. A user should be aware of the categories and how they are relevant to the device application to help with the correct instrument selection process.

Irrespective of the category that the device fits into, it is a requirement that particulate monitoring equipment has a 'type approval' known as a (QAL1 certificate), issued by an official test laboratory – Monitoring Certification Scheme (MCERTS) in the UK and TUV in Germany. A type approval is issued following several highly controlled tests to prove the reliability of the test equipment. Following installation on site, the equipment is required to be calibrated and its suitability for intended purpose should be demonstrated with a (QAL2 certificate). The results obtained using the standard reference method, taken by an accredited laboratory, are used for calibration and accuracy checks (Nathalie, 2015).

3.1 Continuous or Periodic Sample

A continuous particulate monitor measures a parameter that changes depending upon the concentration of particulate in a gas stream and can be used not only to measure particulate concentration but also to monitor processes to give a qualitative analysis of emissions (Averdieck, 1994; Buonanno et al., 2009). A periodic sample is taken over a period of time and will only give a mass concentration measurement result for a certain point in time rather than continuous real time monitoring (Nussbaumer et al., 2008).

3.2 In-Situ or Extractive

In situ measurements are taken on the stack itself using an instrument usually attached to the stack via flanges, extractive measurements remove a representative sample from the stack and analyse the sample externally (Kanchan, 2018). Some devices used for in-situ measurements can be adapted and applied extractive sampling. Particulate and Compliance Emission Monitoring (PCME) manufacture two products that operate using the same forward scatter laser technology, one is designed for in-situ and the other extractive measurement allowing for measurements to be taken on wet stacks where water droplets may be present (PCME Ltd, 2019a, 2019b).

3.3 In-Stack or Out-stack

This usually refers to isokinetic sampling and refers to the location of the filter in the sampling system. In-stack sampling locates the filter housing and filter inside the stack whereas out-stack sampling locates the filter outside of the stack (Volker Lenz, Daniela Thrän, 2018) and is used when there may be water droplets present in the sample.

3.4 Direct or In-direct

Direct measurements respond to changes in the mass of collected particles using the laws of physics whereas indirect measurements respond to changes of particle characteristics rather than mass (Meyer, 2004).

3.5 Measurement principals

Generally, there are three core principals currently used for monitoring particulate. These three primary approaches for determining the particulate content of a gas include (Engdahl, 2012):

- The direct measurement of particulate contained in a known volume of gas is captured on a filter and weighed.
- The measurement of certain physical characteristics of the particulate such as electric charge can be related to the mass of the particles in a known volume of gas.
- The attenuation of an energy source such as light or radiation passing through the aerosol or mass of particulate can be related to the concentration.

4 Measurement Techniques

The question may arise as to why there are so many techniques to measure particulate emissions. As Engdahl (Engdahl, 2012) states, it would be a formidable task to develop an instrument which will instantaneously and accurately record the concentration of particulate in a stack over a wide range of operating conditions. Issues arise with monitoring instruments when the limitations are not fully understood, highlighting the importance of knowing the characteristics of the application when choosing a suitable device. A study by Oetari (Oetari et al., 2019) found that plants using the same fuel had different emission profiles depending upon the design of the treatment process, highlighting the need to understand the emissions profile and find a measurement device to suit. Jahnke (Jahnke, 2000) explains that there is currently no best fit solution to particulate monitoring with a problem being that there is no method available to measure mass both directly and continuously.

An article by Mills (Mills, 1999) details the issues surrounding continuous stack particulate monitors, stating that they suffer from potential inaccuracies as they do not directly weigh particulate and must be periodically calibrated using the reference method. Although, despite its status as the reference method, using gravimetric analysis can be very laborious, time consuming and not always repeatable. Chung (Chung et al., 2001) explains that using traditional filter based methods to measure particulate has a disadvantage as they do not offer information in real time as the process requires long sample times. These problems are relevant when using filter-based sampling in both stationary and ambient particulate monitoring.

Meyer (Meyer, 2004) states that in order to measure particulate matter mass concentration directly, particulate needs to be collected and weighed, and that the elimination of mass calibration uncertainty is only possible when using sensors based upon first principal physical laws (direct mass measurement).

Averdieck (William Averdieck, 2015) reports of two particular cases where the wrong test instruments were fitted to industrial applications causing cost implications. The first being a vehicle catalyst plant in the UK where the minimum detection level of the fitted opacity measurement instrument was 100mg/m^3 and the prescribed emission limit value was 1mg/m^3. This was using an opacity meter that could not detect low enough values to be of any use for the application, resulting in the need to replace and re-calibrate a new instrument. The second case was a pharmaceutical company’s clinical waste incinerator in the UK where an optical measurement device was installed to measure emissions but due to the low emissions value of 2mg/m^3 and a small optical path length, the instrument had no response to the low values and was unable to be calibrated. This highlights the need to correct application of measurement technique.

Technology	General Principals	Detection Limits	Measurement Range (mg/m^3)	Advantages	Disadvantages
Gravimetric Analysis (Standard Reference Method)	Requires isokinetic sampling to obtain representative sample. Sample is collected on a filter, taken to a laboratory for weighing before and after sampling to determine particulate in stack. Probe is moved in different positions over a time period to achieve a representative sample in accordance with legislation	Analysis is difficult where emissions are less than 10mg/m3	>10,000	Suitable for processes with changing conditions. Reference method for calibration of alternative measurement methods, detailed guidance on process methodology is available in legislation	Labour intensive, manual process, equipment is heavy, not capable of continuous measurement, gives no feedback on process
Opacity Scintillation	These devices measure the temporal variation or light scintillation in its intensity, they do not measure mass of particulate directly and require calibration which is dependent upon particle size, composition, shape, colour, and refractive index.	Generally, not used in applications where emissions are less than 10mg/m3	>1,000	Suitable over a wide range of stack diameters from 0.3 - 18m, generally unaffected by particulate contamination	If process or emissions conditions change, re-calibration is required, requires regular calibration, sample chemical analysis not possible
Standard Opacity	These devices measure the attenuation of energy of an optical light source transmitted through a flue gas, with the attenuation being proportional to the particulate in the stack. They do not measure mass of particulate directly and require calibration which is dependent upon particle size, composition, shape, colour, and refractive index	Generally, not used in applications where emissions are less than 10mg/m3	>10,000	Suitable over a wide range of stack diameters from 0.3 - 18m, generally unaffected by particulate contamination	If process or emissions conditions change, re-calibration is required, requires regular calibration, sample chemical analysis not possible
Back Scatter	Back scatter devices measure the amount of light scattered back from particulate in the stack and do not measure mass of particulates directly, requiring calibration with the standard reference method	10mg/m3 and above	>1,000	Suitable for stack diameters up to 8m	Not suitable where process conditions are subject to change, requires calibration
Forward Scatter	Forward scatter devices measure the amount of light scattered forward from the particles in the stack and do not measure the mass of particulates directly, this therefore requires calibration with the standard reference method	10mg/m3 and above	>200	Suitable for stack diameters up to 8m	Not suitable where process conditions are subject to change, requires calibration
Beta Attenuation	Beta attenuation is undertaken under isokinetic conditions, where a representative sample is extracted from the stack and deposited onto a filter tape which moves sequentially on a roll, this means that the filter cannot be removed for chemical analysis	2mg/m3, but calibration at this level is unachievable with the standard reference method	>10,000	Can measure at low concentrations <10mg/m3, suitable in changing process conditions, suitable for stack diameters up to 18m	Calibration is required, chemical analysis not possible, expensive, high maintenance requirements
Triboelectric	Tribo electric systems measure the magnitude of DC current produced by particles colliding and rubbing against the sensor inserted in a stack. Can be affected by a build-up of particulate on the probe. The amount of DC current produced is proportional to the particulate concentration in the stack	Measurements below 10mg/m3 are possible but calibration at this level is not possible	>1,000	Low initial cost, ideal for indicative monitoring	Highly sensitive to changes in process and particulate conditions, calibration required, suited to smaller diameter stacks
Electrodynamic	Probe electrification is a measure of contact charge transfer, measuring charge transferred to a probe in the stack. Measures the AC current produced which is directly related to the concentration of particulate in the stack. The AC signal is measured, analysed and an output given in mg/m3	Measurements below 10mg/m3 are possible but calibration at this level is not possible	>1,000	Low initial cost, ideal for indicative monitoring, less affected by particle build up on probe than triboelectric	Highly sensitive to changes in process and particulate conditions, calibration required, suited to smaller diameter stacks
TEOM	The TEOM is a loaded oscillator and electromechanical device that measures a change in frequency of a vibrating oscillator which reduces as mass of particulate builds up on a filter located at the end of the oscillator	Measurements below 10mg/m3 are possible but calibration at this level is not possible	>200	Not affected by changing conditions, filter can be removed for chemical analysis	Requires an intensive maintenance program, high cost, requires calibration

Table 1 Technology Overview of Features

4.1 Isokinetic Sampling – Gravimetric Analysis (Standard Reference Method)

The process of using isokinetic sampling with gravimetric analysis is referred to as the reference method, being the standard method to calibrate continuous emissions monitoring systems. This applies worldwide, although other variations in name may be used including, reference method, standard reference method (SRM) and correlation method. Relevant standards for Isokinetic Sampling include: BS EN 13284-1 and USEPA Method 5 (BSI Standards, 2017a; US - EPA, 2017).

Standard reference method results do not give indication on the performance or control of the combustion process, as it is usually performed annually or biannually depending upon legislative requirements (Beutner, 1974; Jahnke, 2000). As the name suggests, this is a sample method and therefore for the results to be meaningful the tested sample must be representative of the total emissions (Vallero, 2008). This does however allow for the filter can be taken to a laboratory for elemental analysis of the sample, something that can be difficult with other techniques. Ge (Ge et al., 2001) successfully carried out a study of stack gas emissions where the mass of the sample on a filter was weighted and then taken to a laboratory for elemental analysis.

Test results of particulate concentration are meaningless without calibration of the system in its operating conditions against a reference method. With gas analysis, a known calibration gas can be used for the process, whereas with particulate, no viable, independent, particle mass concentration standard exists. The reference method is the only available method for calibration (Apex Instruments, 2008; Averdieck, 2011; Jahnke, 2000) and this does not come without its own issues as accuracy of isokinetic sampling has to be accurate, reliable and repeatable for the results recorded from the system in service to have credibility.

Due to increased legislation, particulate emission sources are becoming cleaner and are controlled to a much lower concentration level than ever required before, in some cases down to <5mg/m^3 (World Health Organization, 2015). However, manual test methods are difficult to use on low concentrations (<10mg/m^3) of particulate.

The manual gravimetric analysis test method was first introduced in around 1970 and as Jahnke (Jahnke, 2000) explains, there can be an expectation that, as this is a manual reference test method, the results must be accurate. This is not always the case and some of the problems are: the inability to accurately measure low particulate concentrations, and poor experimental technique – leading to inaccurate results. Engdahl (Engdahl, 2012) reported that isokinetic sampling with gravimetric analysis is a tedious task and is of uncertain accuracy due to so many areas where losses can influence the process. Figure 2 and Figure 3 show the detail of typical Isokinetic Sampling equipment; the weight of this equipment can be up to 100kg.

Part of the process of isokinetic sampling is to report results in standard conditions. Measurements are not taken in standard temperature and pressure conditions, and therefore a conversion will be required (Tiwary and Colls, 2010; Volker Lenz, Daniela Thrän, 2018). As temperature and pressure change, the volume of the gas also changes, even though it still contains the same amount of particulate. The standard conditions of a dry gas for reporting reference method are 101.325 Pa and 273.15K (BSI Standards, 2017b; O'Brien, 2019).

The principal of isokinetic sampling is, that a nozzle (designed to offer minimum resistance and disturbance) is installed parallel to the gas flow; the sampling flow rate is designed to reduce disturbance to the original flow. During sampling, the sample flow rate is adjusted so that the velocity at the nozzle is equal to the velocity in the duct (Arouca et al., 2010). The mass of the particulate is drawn through a filter which captures the particulate (Lim et al., 2015). The volume of gas that is drawn through the filter must also be measured. These values are used to calculate a mass concentration reading subject to a representative sample being obtained (O'Brien, 2019).

The measurement of particulate where moisture is present is particularly challenging, where this is the case when using the standard reference method extra measures are required. Out stack filtration is best suited to wet samples where the filter and sample can be heated to vaporise any droplets present (BSI Standards, 2017a). BS 13284 states that the filter must be conditioned, also detailed in a study by Kuo (Kuo et al., 2015). The filter should be dried for at least 1hour before sampling at a temperature of at least 20°C above the maximum temperature reached during sampling. The filters are to be cooled to ambient temperature in a desiccator located in the weighing room for at least 4hours.

Isokinetic sampling is usually (for the purposes of calibrating continuous emissions monitors) undertaken by accredited laboratories. These laboratories must know the uncertainty associated with the measurements to minimise losses and increase accuracy. In a report issued by GDF Suez, Laborelec (Nathalie, 2015) they state that at low concentrations (10mg/m^3), calibrating particulate monitors is becoming increasingly challenging.

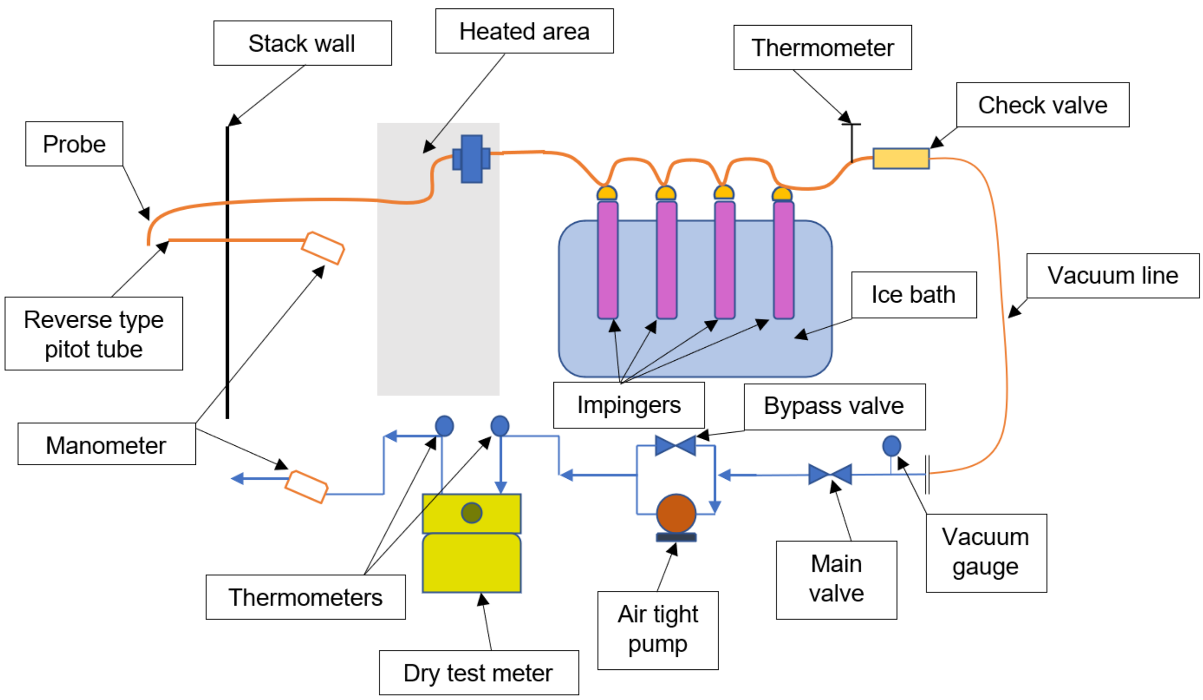

Figure 2 Typical Isokinetic Sampling Equipment (O'Brien, 2019)

Using isokinetic sampling a representative sample is collected on a filter media, located either in-stack or out-stack depending upon the application. Gravimetric analysis is the process of analysing the particulate collected, where the filter media is weighed before and after the sampling procedure to calculate the mass of particulate in a known volume of gas, as explained by Lee who details how this process was implemented during a study to accurately measure particulate matter emissions (Lee et al., 2020).

Figure 3 Clean Air Isokinetic Sample Train (Clean Air Instrument Rental, 2015)

Losses must be minimised as much as possible to obtain a representative sample and maintain high accuracy in particulate measurement systems. A study completed by Zhu (Zhu et al., 2018) detailed the many factors that can affect the loss of particles in the sampling lines of emission monitors. These factors include temperature difference between hot sampling gas and the pipe wall, and the surface roughness from the pipe itself or the particles. Combining all the possible factors, losses in the sampling lines of a particulate monitor can reach 69% after 0.2 seconds for PM10; smaller particles have lower percentage losses. Processes can contain semi-volatiles where particulate can form solid matter at low temperature but appear in a gaseous form at higher temperatures. Effects from semi-volatiles can be minimised by carefully selecting the temperatures during isokinetic sampling by considering the plant process conditions, the sample temperature and the due point of the gas. To achieve accurate results the effects of semi-volatile material should be accounted for, BS13284-2 (BSI Standards, 2017b) details the procedure for accounting for semi-volatiles as follows; dry the collected dust at the conventional temperature for the SRM measurement and weigh the dry samples. Re-dry the collected dust at 160°C and re-weigh the samples. All results are presented in the calibration report to include all particulates.

The standard BS EN 13284-2 (BSI Standards, 2017b) states that the sampling velocity should be within -5% to +15% of the isokinetic velocity but should be as close as possible to minimise losses. Figure 4 taken from work completed in BS13284-2 (BSI Standards, 2017b), indicates the influence of particle size and nozzle diameter and their combined effect on the error due to non-isokinetic sampling with constant flow rate. The first graph indicates the influence of particle size '*d'* and the nozzle diameter between 6mm and 32mm and their combined effect on the error '*e'* at 20% under-isokinetic sampling. The second graph indicates the influence of particle size d and nozzle diameter between 6mm and 32mm and their combined effect on the error '*e'* at 20% over-isokinetic sampling.

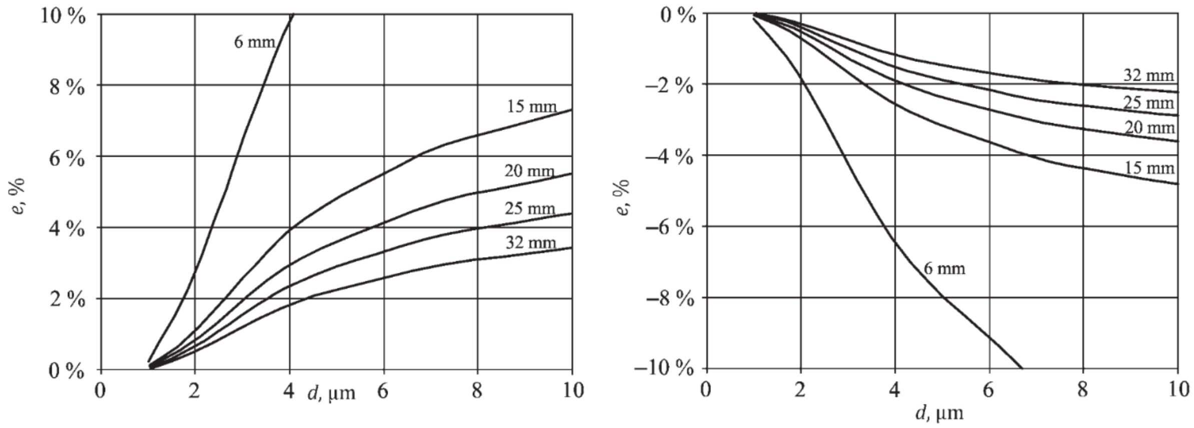

Figure 4 Effects of Over and Under Isokinetic Conditions for 5 Nozzles (6mm, 15mm, 20mm, 25mm and 32mm) (BSI Standards, 2017b)

Permission to reproduce extracts from British Standards is granted by BSI Standards Limited (BSI). No other use of this material is permitted. British Standards can be obtained in PDF or hard copy formats from the BSI online shop: www.bsigroup.com/Shop

4.2 Probe Electrification

Probe electrification systems utilise a probe installed inside a section of a stack that is in such a position to measure the most representative profile of particulate emissions. Figure 5 details how a probe would be inserted into a stack to achieve a representative sample. As explained by Averdieck (William Averdieck, 2014), the working principal of probe electrification technology is based on the measurement of electrical signature derived from the interaction of the particles and probe installed in the stack.

There are two common methods of measurement available (Yong Yan, 2005) but both methods have very different measurement characteristics. The signal in electrodynamic measurement uses the induced frequency response from variations in the distribution of particulate passing the probe, whereas with triboelectric, the signal comes from the total number of particles impacting the probe. Averdieck (William Averdieck, 2014) explains that triboelectric systems measure and amplify the magnitude of the DC signal produced when particles in the stack collide with or rub against the grounded sensor inserted into the stack. This DC signal can be dependent upon many factors, the most important being the concentration of particulate but other factors that can affect results are: the amount of charge transfer, the particle impact energy, probe material and the type and characteristics of particles. Electrodynamic dust monitors measure AC current as a result of a charge induction. As the charged particles pass the grounded sensor, the measured AC current is directly related to particulate concentration.

The term electrodynamic generally stresses the fact that the charge is generated from movement of particulate, where the term triboelectric suggests that the particulate is charged due to friction or direct contact with the electrode (Yong Yan, 2005).

There are probe electrification products available to measure mass concentration limits as low as 0.1mg/m^3 (Averdieck, 1994; Yong Yan, 2005) making this method of measurement very appealing to certain applications. However, sensitivity is considerably higher than that of any opacity monitors, and an important consideration is that accurate calibration of a system at such low concentration (<10mg/m^3) levels is extremely challenging, if at all possible. Care should be taken when determining the reliability and accuracy of such low readings if an accurate calibration process is not possible. Nevertheless, Yan (Yong Yan,

2005) explains that probe based electrostatic particle monitors are suitable for installations on stack sizes of 50mm – 6m, making them a versatile device.

The movement of particles in an industrial plant generates an electric charge. As described by Yan (Yong Yan, 2005), (Yan and Ma, 2000), the electrification of particles is expected when they come into contact with other surfaces. The electrostatic charge is due to collisions between particles, the surface of the stack, and friction between particles and the air stream. The amount of charge is dependent upon physical and chemical properties of the particles as well as external influence such as humidity and temperature.

Measurement issues with triboelectric and electrodynamic devices can be affected by changes in particle size distribution, changing particle type, changes in particle characteristics or changes in charge on the particulate (Rahmat and Tajdari, 2011) this can include the presence of moisture in a wet stack. If the application is subjected to any of these changing conditions then probe electrification may not be the best method of measurement (Yong Yan, 2005). An example application could be an incinerator where fuel type is subjected to change and electrostatic precipitators are used. This is confirmed by Yan (Yong Yan, 2005) who explains that a limitation of both methods of probe electrification is that they are sensitive to changes in physical and chemical characteristics of particulate as well as to changes in humidity and temperature of the source.

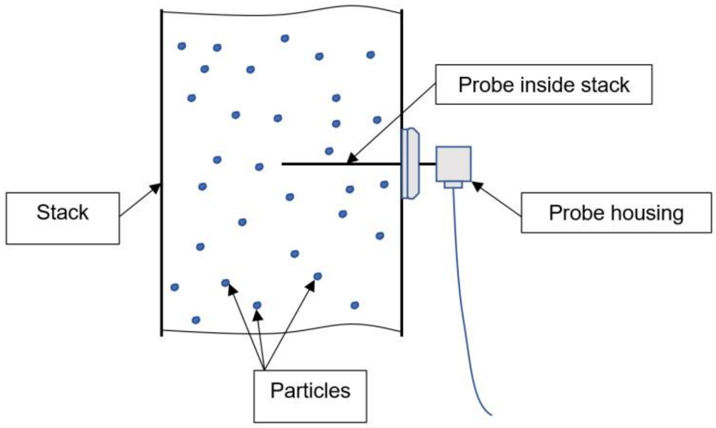

Figure 5 Probe Electrification System (Yong Yan, 2005)

4.2.1 Electrodynamic System

Probe electrification is a measurement of contact charge transfer, measuring charge transferred to a probe inserted into a stack. When two materials make contact, due to the flow of particles in a stack there is a net transfer of electrons from one material to another (Jahnke, 2000; Yan and Ma, 2000). Electrodynamic particulate monitors measure alternating current; the AC current produced is directly related to the particulate concentration. Two types of interaction take place to produce the charge – direct collision with the probe and charge induction where charge on the particle repels charge in the probe as it passes in close proximity. (William Averdieck, 1997).

The AC signal is measured and analysed by the measurement device to give an output in mg/m^3 which can then be calibrated against the SRM to give meaningful results. This signal can be amplified to higher levels than with the triboelectric method. Electrodynamic systems are not affected by build-up of particulate matter on the probe unlike the use of triboelectric measurement. In electrodynamic measurements, triboelectric current is also produced but is filtered out (William Averdieck, 2014).

4.2.2 Triboelectric System

In triboelectric systems the magnitude of DC triboelectric current, produced by particles colliding and rubbing against a grounded sensor inserted in a stack, is measured and amplified (William Averdieck, 2014).

Triboelectric devices detect three separate effects when particles impact or pass close to the probe. Castellani (Castellani et al., 2014) describes the three effects as: 1- a particle striking the conductor causes a charge transfer to take place between the particle and conductor, 2 - a particle striking the conductor rubbing on the surface causing a frictional charge, 3 - charged particles passing close to the conductor inducing a charge of equal and opposite magnitude. The charge generated by 1 and 2 are dependent upon velocity, mass and charge history and the third is an inductive charge.

Triboelectric systems can be affected by a build-up of particulate on and around the probe in the stack and have limited sensitivity to submicron particles which do not contribute proportionately to mass (Nader, 1975). This then creates unreliability with readings and requires a regular maintenance program to minimise inaccuracies due to contamination of the probe (PCME Ltd, 2016).

The amount of DC current measured is related to the particulate concentration, although other parameters can affect the charge transfer. Averdieck (William Averdieck, 2014) explains the factors that can affect measurements to be, the type of particulate which is dependent upon the fuel source; the energy of the particle; the material of the probe; velocity; and any contamination that may build on the probe surface. A typical triboelectric probe is shown in Figure 6.

Figure 6 Auburn Systems Triboelectric Probe

4.3 Opacity

As a beam of light hits a particle, it is either scattered by reradiating it in all directions or absorbed by transforming it into other forms of energy (Beutner, 1974; Giechaskiel et al., 2014). This characteristic of particulate can therefore be used as a technique to measure mass concentration. The size, shape and colour of particles as well as the type of light and receiver will determine how this light behaves in opacity measurement. Using optical techniques to measure the mass concentration of the particulate is not a direct measurement (Patashnick and Rupprecht, 1991; Time et al., 2018), and a calibration procedure is required for all optical measurements. Opacity measurement instruments measure the reduction in light passing through the stack due to particulate

As explained by PCME (PCME Ltd, 2016), laser scatter systems are now replacing standard opacity instruments due to increased performance and ease of installation as they can be installed in single point configuration. Manufacturers state that they can be used to measure low concentration at levels of particulate <10mg/m^3, however, this would still have to be confirmed via calibration as with all methods of continuous emissions monitors. This brings into question the reliability of results at these levels due to problems associated with the standard reference method at low levels.

There are two methods of opacity measurement used in stack emissions testing. Both use similar methodology but interpret measurements in different ways to output a mass concentration reading. The two methods are traditional opacity and ratio-metric opacity (Chen et al., 1998).

Opacity and light scatter techniques are sensitive in applications where water droplets may be present and therefore care should be taken when choosing a measurement technique for use in these environments. It is possible to use optical techniques to measure particulate matter in wet stacks where moisture droplets are present, but different techniques are required, most commonly extractive techniques. One way to remove the water droplets from the sample is to heat the sample. However, the additional process increases losses in the sampling equipment and therefore an important design consideration here is to ensure that the sample remains representative.

4.3.1 Traditional Opacity

Traditional opacity measures the attenuation of energy of an optical light source transmitted through a flue gas (Chen et al., 1998). Yet, The Environmental Agency (Environment Agency, 2017b) state that opacity meters are not suitable for concentrations less then 10mg/m^3 measurements, making them unsuitable for certain applications.

The light from an opacity device can pass through the stack by transmission, be scattered by particles, be absorbed by particles or be reflected by particles. An increase in particulate will give an increase in light energy attenuated.

Figure 7 details how opacity can be measured according to the concentration of particulate in a stack.

The receiver in an opacity meter measures the decrease in light intensity due to absorption and scattering as the beam crosses the stack through the particulate matter. As explained by Castellani (Castellani et al., 2014), the principal of operation of an optical system is that the receiving optics measure the reduction in light intensity. This reduction in light translates to a mass concentration output in mg/m^3.

There are two types of configuration of opacity monitors, single pass and double pass. Double pass devices use a reflector on the opposite side of the stack to the light source. Single pass devices have a light source and detector on opposite sides of the stack. Benefits of double pass include having no electronics on the reflector side of the stack resulting in an easier maintenance procedure.

Castellani (Castellani et al., 2014) confirms that opacity meters used to measure particulate matter should use a red or near infrared light source and that opacity measurements are dependent on particle size, composition, shape, colour and refractive index. These characteristics will change depending upon fuel type and application, emphasising the need for accurate and regular calibration.

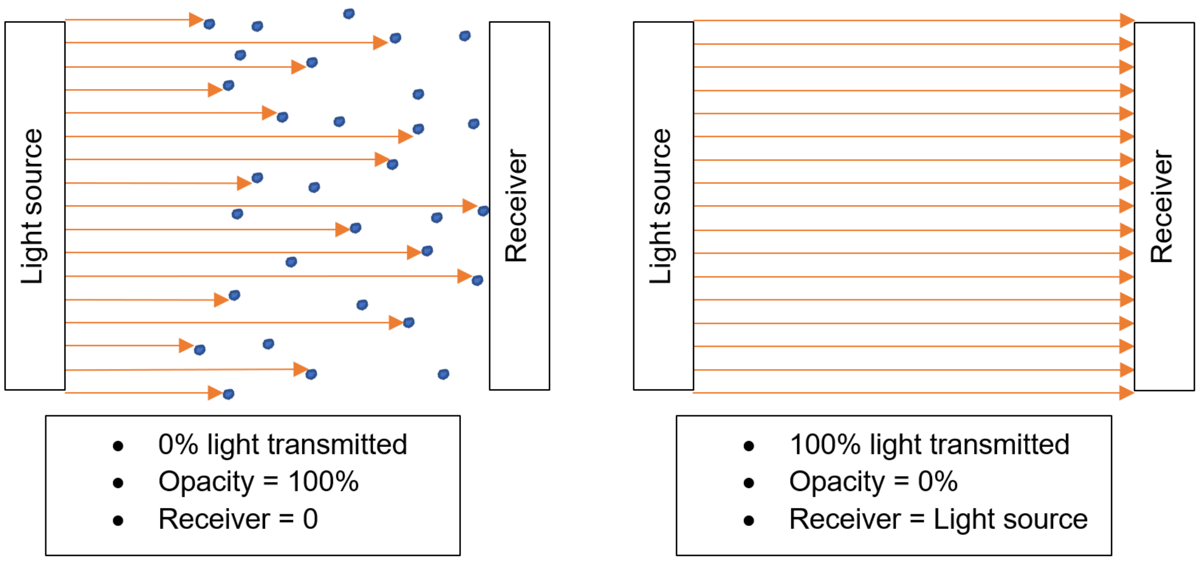

Figure 7 Opacity Technology

Opacity monitors can be used to measure particulate mass concentration which is done via a calculation from the opacity measurement, however, there is a lower level of measurement making them insufficient when measuring concentrations lower than 10mg/m^3 accurately. The relationship between opacity and particulate concentrations are defined by the Beer-Lambert Law.

4.3.2 Ratiometric Opacity

Where traditional methods of opacity measure the intensity of light received, ratio-metric methods measures the ratio of signal scintillation to absolute light intensity (Averdieck, 2011; Kanchan, 2018). Ratiometric opacity devices do not measure the light beam intensity but the temporal variation, or light scintillation in its intensity (Chen et al., 1998). Castellani (Castellani et al., 2014) describes the main advantage of this method over traditional opacity methods as being that it is unaffected by lens contamination, therefore reducing maintenance of the unit. The reduction in light intensity and the reduction in intensity caused by lens contamination are affected by the same proportion; the device is therefore unaffected by contamination up to approximately 90%.

The PCME stack 602 is a ratio-metric opacity particulate monitor measuring the rate of change of light. The solution to contamination issues are explained by PCME (PCME Ltd, 2019c); their ratio-metric method has significant advantages in terms of reliability and resolution over traditional opacity measurement techniques, as it avoids problems associated with the fouling of the lens in a traditional device.

The principal of operation is that the instrument measures the ratio of temporal variation in intensity of the light; this is known as optical scintillation. Optical scintillation is caused by variations in the atmosphere that the light passes though. These irregularities produce optical effects on a light source (PCME Ltd, 2019c; Rary et al., 1965). When used as a particulate measurement instrument, the higher the concentration of particles in the stack are and therefore in the light path, the greater the range in variation of light.

Averdieck (Averdieck, 2000) explains that ratio-metric opacity also known as dynamic opacity is only capable of resolving particulate concentrations as low as 2.5mg/m^3 but calibration makes this difficult to achieve less than 10mg/m^3. This technology can also be applied to a large concentration range as it *is* suitable for concentrations up to – 1000mg/m^3.

Figure 8 taken from PCME's Stack 602 datasheet shows that light intensity and the variation in intensity are affected by the same proportion (Castellani et al., 2014).

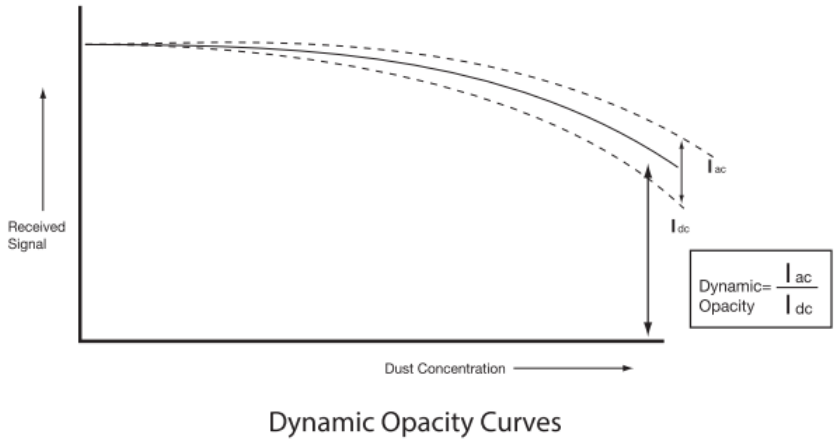

Figure 8 Dynamic Opacity Curves from PCME Stack 602 (PCME Ltd, 2019c)

4.4 Loaded Oscillator

The loaded oscillator is an electromechanical device that has been developed on the principal that the frequency of a vibrating oscillator will reduce as the mass of the element increases (Jahnke, 2000). Aside from the direct gravimetric measurement technique, a loaded oscillator is one of the most direct means of measuring particle mass. Janke (Jahnke, 2000) explains that although this technology has been used for a long time, there are a number of problems relating to cleaning and recalibrating the vibrating element.

The principal of operation is that a representative sample is isokinetically taken from the stack and sampled through a filter located on top of a hollow tube which oscillates in a temperature controlled housing (Gonnet and Forges, 2004). A carefully controlled vacuum is applied to the opposite end of the hollow tube and as the gas flows through the tube, the particulate is captured on the quartz filter (Wang et al., 1983). The changed in frequency of the oscillating tube is measured, and the reduction is proportional to the mass of particulate (Patashnick and Rupprecht, 1991; Wang et al., 1980).

A Tapered Element Oscillating Microbalance (TEOM) monitor detailed in Figure 9 provides a continuous measurement of collected particulate mass. The filter collects the particulate from the sample and, as in alternative filter-based measurement techniques, can suffer from the same losses ("TEOM Technology for Particulate Matter Measurement - UK," 2019). This can include the loss of semi-volatile material collected during sampling. As explained by Soysol (Soysal et al., 2017), heating the system is necessary for the accuracy of the sensor due to its sensitivity to temperature, however, this does increase the losses in semi-volatile material.

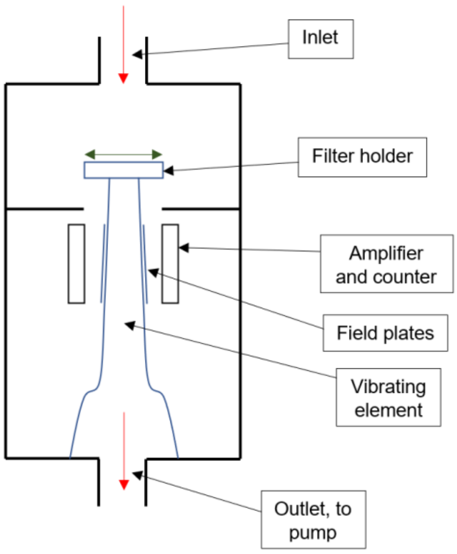

Figure 9 TEOM Element (Tiwary and Colls, 2010)

A TEOM monitor allows a sample to be collected from a stack or duct while automatically maintaining isokinetic sampling conditions. A filter is attached to one end of the mass transducer allowing the collected particles to be weighed continuously, resulting in a real-time measurement of the mass concentration. Gonnet (Gonnet and Forges, 2004) continues by explaining that tracking the frequency of the oscillator provides the mass rate and when this mass rate is combined with the sample flow rate through the filter, mass concentration can be directly calculated.

The TEOM is specific to mass measurement loading, and even though the oscillating frequency is directly proportional to mass, there can be significant systematic errors. To reduce the errors, the oscillating element is maintained at a temperature of 50°C (Elmes and Gasparon, 2017), even though this temperature is high enough to evaporate volatiles from some particulates, reducing the mass and therefore reducing the accuracy. Additional pre-treatment of the sample can reduce some volatilisation errors (Tiwary and Colls, 2010).

4.5 Beta Attenuation

Beta radiation devices are commercially available (Eiseman, 1998) and use an isokinetic technique to extract a sample from the flue or duct; this sample is deposited on a glass fibre filter tape. The filter tape is wound on a roll moving sequentially so that a small spot of particulate matter is collected and analysed (Jahnke, 2000). Figure 10 shows how the particulate is collected on the filter tape before moving to the Beta attenuation analysis. The filter media is tested before any particulate is deposited and used as a base line. This figure is then subtracted from the final measurement result to calculate the difference between the two measurements. A typical beta attenuation monitor is detailed in Figure 11.

Beta attenuation systems are based upon the correlation between the intensity of the Beta radiation and the concentration of particulate on a filter paper (Nader, 1975). Beta gauge samplers continually measure particulate by extraction. The extracted sample is applied to a filter tape and analysed via a Beta gauge with the result converted to give a mass concentration reading. The sampling duration is usually programmable (Richards, 2000) and will determine the mass concentration detection limit; at high concentrations the duration is kept low (Nathalie, 2015) to avoid sampling excessive particulate concentration (Eiseman, 1998).

Castellani (Castellani et al., 2014) explains that the difficulties associated with using Beta gauge measurement devices are the high maintenance requirements, although, they do benefit by not being affected by size, colour changes and size distribution differences (Eneva, 2018; Richards, 2000). These difficulties are expanded upon in a presentation by Cemtek ("Cemtek Environmental, Inc. Particulate Matter Monitoring Technologies and Detection Principles CEMTEK Environmental," 2011); the installation process is difficult, the devices are expensive and the operating costs are high.

The radiation absorbed and scattered by the particulate collected for analysis is dependent upon its composition. The absorption of beta rays depends upon the exchange of energy with the electric field of electrons in the particulate. Jahnke (Jahnke, 2000) explains that the exchange is only slightly dependent upon the atomic number for most of the particulate found in stationary source emissions due to the electron density being similar, where the electron density is equal to the ratio of the atomic number to the atomic weight. If the atomic number is relatively constant the attenuation of the radiation can be successfully used to provide a measure of the mass of the material collected.

As Jahnke (Jahnke, 2000) explains, the advantage of using Beta attenuation is that this method can be used to measure wet gas streams containing water droplets due to using a heated sample probe, although its radioactive source limits its acceptance in industrial applications, as confirmed by Soysal (Soysal et al., 2017). Chung (Chung et al., 2001) explains that while the heated sample line will reduce the effects of water content in the sample, it may bias results where large amounts of volatile particulate is present. Any source of natural or artificial radioactivity can modify the Beta count and therefore influence the accuracy of the results. The main components of a Beta radiation device are the Beta source and the detector, shown in Figure 10. Many detectors can be used to measure Beta count but the most commonly used are the Geiger Muller counter or a photodiode (Castellani et al., 2014).

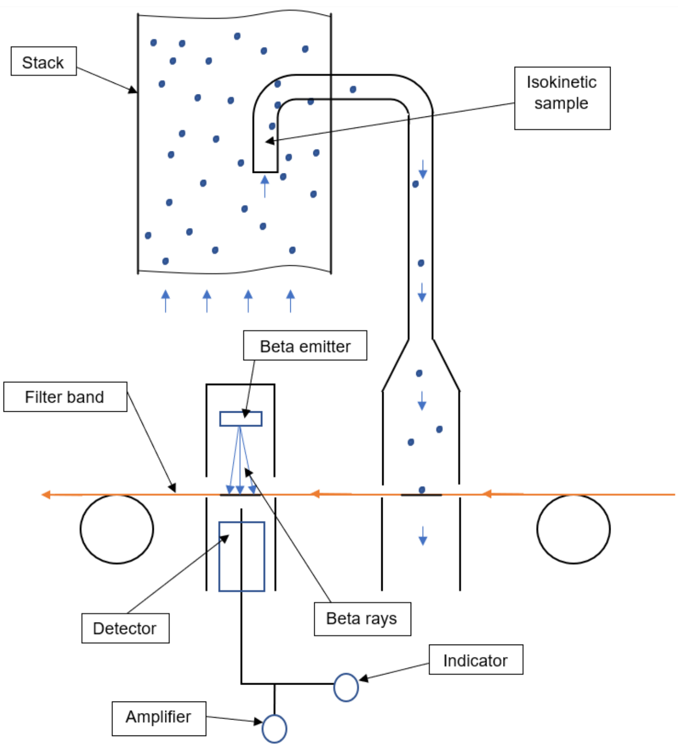

Figure 10 Beta Attenuation Process ("Cemtek Environmental, Inc. Particulate Matter Monitoring Technologies and Detection Principles CEMTEK Environmental," 2011)

The Beta gauge does not measure mass directly and therefore must be calibrated against the standard reference method. Following calibration, a mass concentration reading can be given, usually ranging between 2mg/m^3 – 2,000mg/m^3 (Environment Agency, 2017b).

Although Beta radiation devices are automated sample continuously, the devices cannot be considered continuous in line with MCERTS requirements (Nathalie, 2015) due to the systematic sampling process, they are therefore known as batch samplers (Calcagno, 2001; Engdahl, 2012).

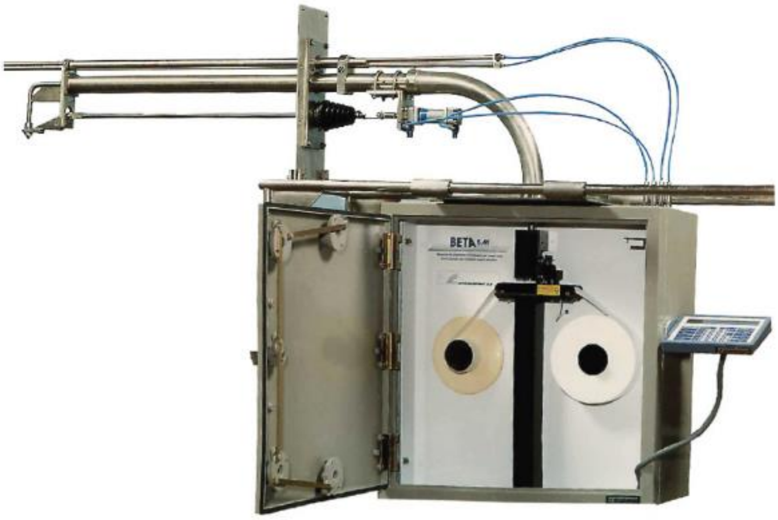

Figure 11 Beta Gauge Monitor (“Stack Particulate Monitor ENVEA - BETA Attenuation,” 2019)

4.6 Laser (Light Scatter)

When a laser beam is directed into the path of particulate it is reflected, refracted, absorbed and scattered in all directions. It is this principal that the light scatter technique uses to determine the concentration of particulate in a stack or duct (Teledyne Instruments, 2003). The amount of light scattered is based upon the concentration and properties of the particles in the path of the light (Bivins, 2000). The properties include, size, composition, shape, colour and refractive index, which, can all change depending upon fuel type (Castellani et al., 2014), although this makes optical sensors strongly dependent upon these properties and can affect accuracy in changing conditions (Liu et al., 2017, 2018). Automatic laser measuring devices can either be forward, backwards or side scatter (which is the way in which the scattered light is measured) and is dependent upon the position of the detector in relation to the path of the light source (Nathalie, 2015). Different angles of detection are chosen by manufactures of equipment for various reasons, including minimising dependence on the particle size distribution and particle refractive index or for instrument design purposes. When the measurement of light absorbing particles is being made, the forward scattering technique is less sensitive to particle size and refractive index changes for particles over size ranges. Whereas side scatter is most sensitive to refractive index but allows for easier design of equipment for in-stack measurements and back scattering is least sensitive to particle size changes. The consideration when using any light scatter instrument when measuring PM mass concentration is that they must be calibrated using the SRM which, should the conditions change, render the measurement inaccurate.

There are two different types of scattering that are observed. These are Rayleigh and Mie scattering. Bivins (Bivins, 2000) explains that when the wavelength of the incident light is much larger than the radius of the particle, 'Rayleigh' scattering is observed, and when the wavelength of the incident light is the same size, 'Mie' scattering will occur (Castellani et al., 2014) – detailed in Figure 12.

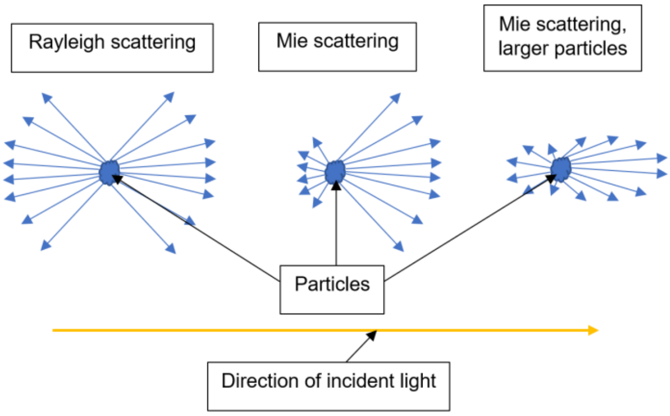

Figure 12 Rayleigh and Mie Scattering (Castellani et al., 2014)

Light scatter devices measure the amount of light that is scattered in a particular direction and will output a signal that is proportional to the amount of particulate matter in the light path (Castellani et al., 2014). Bivins (Bivins, 2000) explains that due to light scatter devices measuring a parameter of particulate, it will require calibration to manual gravimetric samples.

4.6.1 Forward Scatter

PCME (PCME Ltd, 2019a) describe the principal of operation; particles travel through a beam of light causing the particles to scatter light in all directions, light scattered forward being the strongest. The beam of light is transmitted by a laser, through particulate, reflecting off the concave mirror into the beam dump. The concave mirror is focussed onto a quartz rod where scattered light only is transmitted to a light detector; the amount of light received is proportional to the particulate concentration shown in

Figure 13.

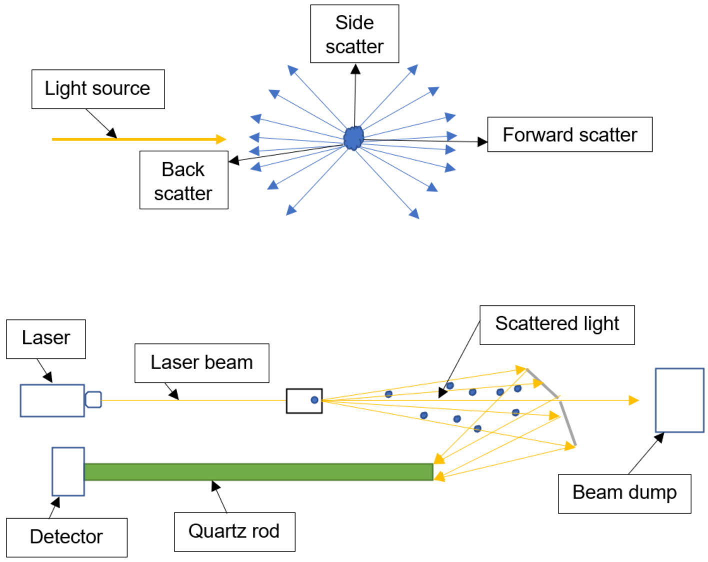

Figure 13 PCME QAL 181 - Principal of Operation (PCME Ltd, 2019a)

A study completed by Chen (Chen et al., 2018) concluded that forward scattering and especially small angle scattering at around 25° is most suitable for low concentrations of around 10mg/m^3 because of the larger sensitivity.

4.6.2 Back Scatter

Back scattering devices are designed to measure particles that are less than 10µm in diameter. Using a wavelength of 900nm and the back-scattering technique, the instrument response is proportional to the cube of the particle radius, giving a direct relationship between particle volume and therefore mass.

PCME ("ProScatter™ Backscatter | PCME," 2019) state the principal of operation of their back-scatter devices; the sensor measures the amount of light scattered back from the particles in the stack, illuminated by a modulated laser. This operation is shown in Figure 14. Application of this technology requires calibration against the standard reference method to give a mass concentration result in mg/m^3 ("ProScatter™ Backscatter | PCME," 2019). Some back scatter instruments do not operate well in high temperatures as it can cause instability issues (Teledyne Instruments, 2003). Back scatter technology is dependent upon the refractive index of the particulate, which can cause issues if the particle characteristics are prone to change (Jahnke, 2000).

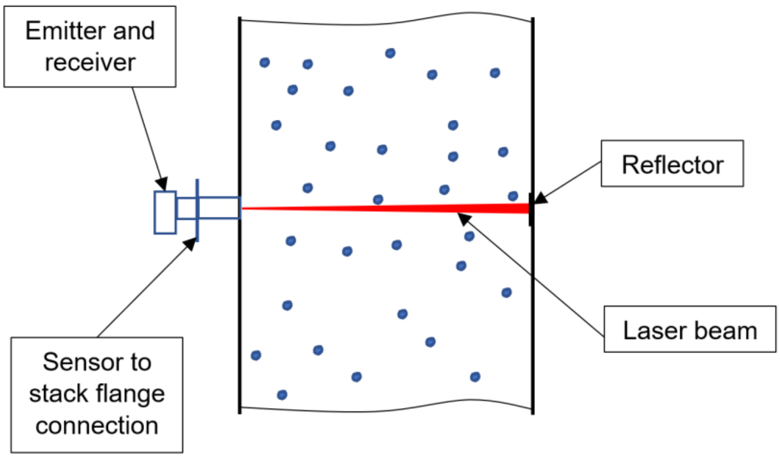

Figure 14 PCME QAL 360 – Principal of Operation (PCME Ltd, 2019d)

4.6.3 Side Scatter

Side scatter devices are capable of measuring low range concentrations <200mg/m^3 of particulate but, as with back-scatter instruments, they are dependent upon the refractive index of the particles and also the particle size distribution (Jahnke, 2000). This is a consideration for application as changes in the fuel, and therefore properties of the particulate, can affect the calibration line of the instrument.

4.6.4 Scatter Technology in Wet Stacks

Although the application of laser technology is affected by water droplets, it is possible to install these devices in wet stacks applying the same technology but using different extractive techniques to sample the gas stream before analysis. Several manufacturers currently produce laser products capable of measurement in wet stack applications. PCME state that their QAL 181 WS model, shown in Figure 15, is suitable for stacks below the dew point and with water droplets (PCME Ltd, 2019b).

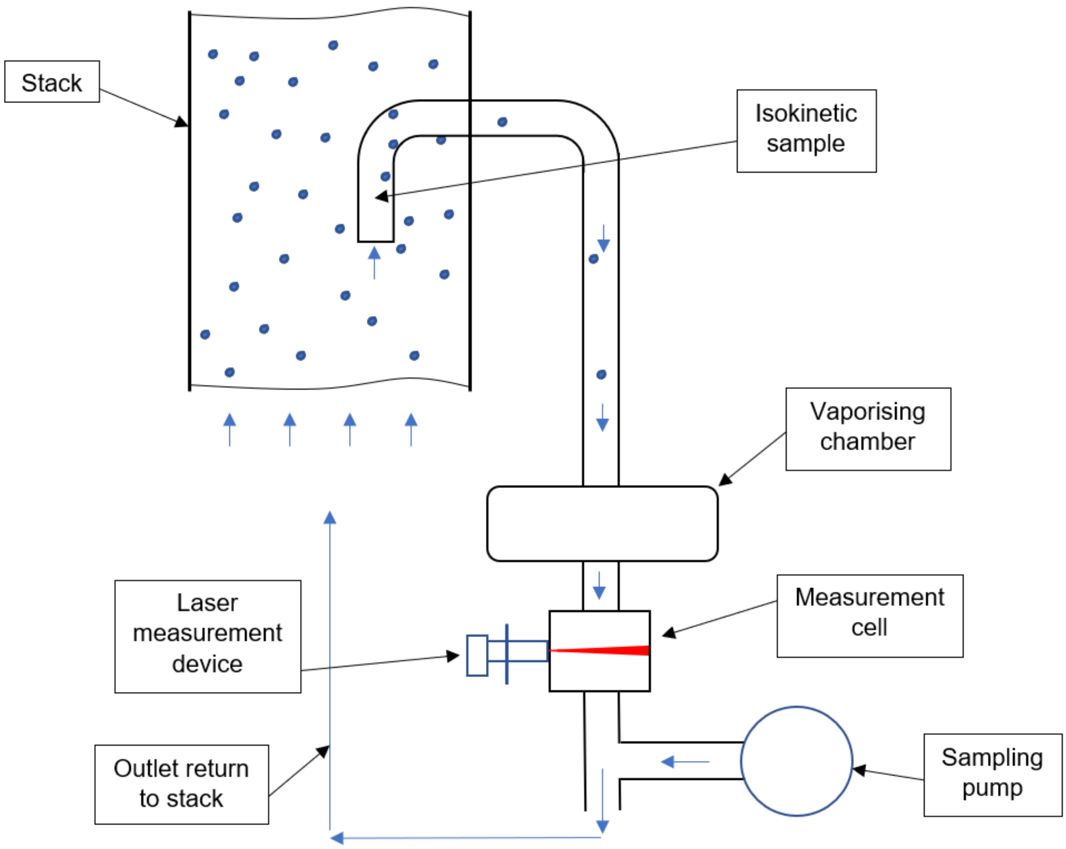

Figure 15 PCME QAL 181 WS – Principal of Operation (PCME Ltd, 2019b)

In a wet stack, a continuous sample is taken from the stack under controlled isokinetic conditions. The sample is heated to evaporate water droplets and condensation above the dew point. The measurement section of the system uses the same laser technology as in-stack testing (PCME Ltd, 2019b).

In certain cases, depending upon the technology used to measure particulate, a mathematical correction calculation may be used to account for the moisture in a stack. This principal will only be successful if used on a process where change in moisture content is minimal.

5 Survey

A survey was conducted as a systematic method of gathering information of the industry regarding the measurement of particulate and the technologies and methodologies used. The survey aimed to gain a deeper understanding of the application and use of the various technologies discussed in this report from a range of experts working within the particulate emissions monitoring industry.

As Jones (Jones et al., 2013) explains, to obtain a representative sample it is important to consider who will be targeted. Therefore, during the design of the survey it was decided that researchers, national regulators, operators, stack testers, independent and in-company test houses and industry specialists (including consultants) would be targeted. The assumption was made, therefore that participants have an understanding of the industry of particulate measurement, this was confirmed in analysis of results with participants confirmation of current job roles Figure 16. 100% also confirming that they understand the health risks associated with dust particulate emissions and 94% having hands on practical experience of dust emissions measurement.

The survey combines the perceptions and views of experts using, designing, maintaining and installing the relevant equipment on a regular basis, with the review of current literature highlighting issues encountered within the industry.

As explained by Ponto (Ponto, 2015), surveys are used for the collection of information from a sample of individuals through their responses to questions. In this review an online research tool was used, similar to that used by Sherman (Sherman et al., 2020) to collect data from participants with the total number of answers for the survey being 732.

The survey was designed with 20 questions for all participants and included both open and closed format questions. Topics covered include: the perceptions of the industry, the roles and experience of participants within the industry, details of the measurement of particulate emissions, requirements for monitoring, and issues/improvements with monitoring equipment.

Participants were asked if in their opinion enough is being done in the industry, and if adequate technology is available to measure particulate emissions. There was a noticeable split within participants' views;

- 50% thought that enough is being done to monitor emissions
- 61% thought that adequate technology is available

Nearly all those who stated that enough was being done to monitor emissions also felt that adequate technology is available and the majority of those who do not feel enough is being done do not feel that adequate technology is available with a small proportion unsure and unable to comment.

Results show that; standard opacity, opacity scintillation, laser, beta attenuation, gravimetric, triboelectric, electrodynamic and oscillating microbalance are the technologies that are currently in use. Gravimetric is the most popular technique, being used by 83% of participants with 30% using laser (light scatter) and an even usage of all other techniques. 75% stated that their single favoured technique would be gravimetric Figure 17 if only one could be chosen but this question did not consider application requirements which will be addressed in the MCDA.

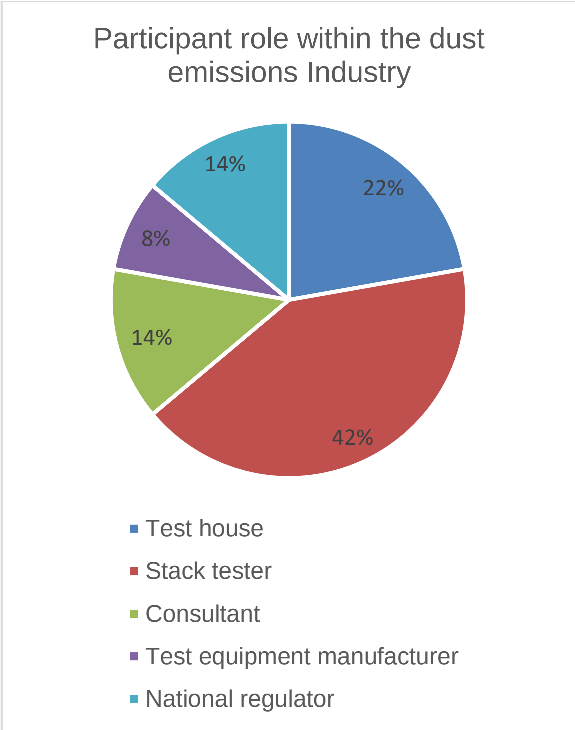

Figure 16 Participant Role within Industry

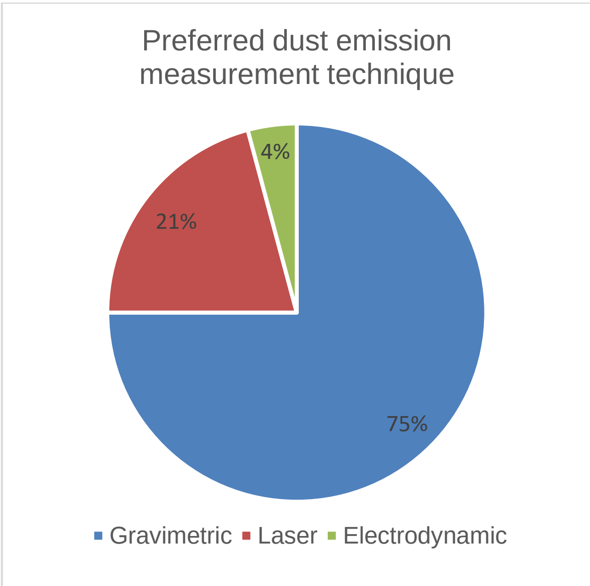

Figure 17 Preferred Particulate Emission Measurement Technique

There is a requirement to measure concentrations of dust particulate down to levels of 5mg/m^3 as emissions limits are being forced lower and cleaner. Participants were asked what measurement technique their preferred choice would be to measure these low concentrations. Figure 18 shows again that gravimetric would be the preferred choice, 34% could not confirm that their equipment is capable of measuring low concentrations.

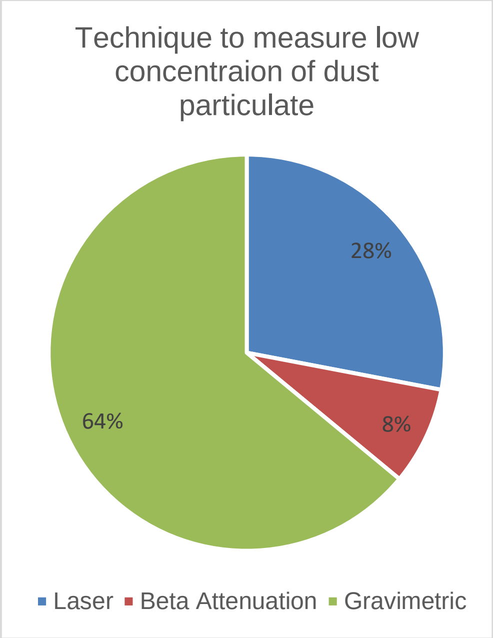

Figure 18 Technique to Measure Low Concentration of Particulate

Participants were given opportunity to openly comment on any problem with particulate monitoring equipment and to discuss any improvements that could be made. There are several themes that have been analysed from the data highlighting the issues and possible improvements to equipment.

Firstly, the difficulty of accurate measurement at particulate below 10mg/m^3 is highlighted throughout the survey results, confirming the findings of the literature review. This problem is now becoming increasingly significant as emissions limit values are driven lower as processes become cleaner. Several experts highlighted and encouraged the need for research into new technologies or methodologies to find suitable approaches to measure at low emission values.

Secondly, those working with the equipment on a daily basis emphasised the need for the equipment to be more 'useable' including a reduction in the size and weight of the equipment, easier maintenance procedures, better connectivity and interface, and increased protection from the elements.

Thirdly, there were two points raised regarding the measurement of the devices; the first; available equipment is not able to efficiently handle any change in the characteristics of particulate emissions. Should a process continually burn the same fuel at the same rate producing the same emissions, the monitoring equipment can provide reasonably accurate results, but when changes in the process occur the results become unreliable. The second; the calibration of devices, especially below 10mg/m^3 is very difficult and results can be unreliable.

6 Multi Criteria Decision Analysis

The process of selecting the most suitable dust particulate monitor is complex due to its multivariate nature, poor decisions can have costly and timely implications. These decisions are rarely a matter of choosing a solution based on the optimisation of a single well defined criteria (Hermans et al., 2007). It is not acceptable to select a device simply because it is a suitable match to one of the many criteria, therefore a more detailed approach should be taken. MCDA is a suitable option to analysing both quantitative and qualitative data for engineers when faced with making a choice between various options (Fontane, 2014), therefore making it ideally suited for comparison of varying technologies against several criteria.

PROMETHEE MCDA methodology was used for this project, the algorithms for the PROMETHEE technique are published in readily available literature (Machrafi, 2012; Ostovare and Shahraki, 2019). PROMETHEE facilitates the ranking and ordering of complex matters (Gunawardena et al., 2013; Lim et al., 2006), which, in this review is particulate measurement techniques for stationary sources. Mathematically the problem is:

$$max\{f_1(a), f_2(a), \ldots f_j(a) \ldots, f_k(a) | \alpha \in A\} \quad (1)$$

Where;

- A is a finite set of n actions
- f_1 to f_k are k criteria
- $f_j(a)$ is the evaluation of action a on the criteria f_j

Assuming that criteria is to be maximised.

PROMETHEE is an outranking method which does not eliminate any alternatives in a pairwise comparison but instead ranks the alternatives according to the criteria and preferences applied by the user with the main advantage being simplicity, clearness and stability (Ostovare and Shahraki, 2019; Sabaei et al., 2015). The process involves assigning preference and weighting conditions pre-selected by the ‘user’ and applying them to the variables (Gunawardena et al., 2013). Weighting is completed separately as weighting techniques are not part of this method, this allowed the use of the industrial survey and literature review to strengthen the weighting process (Fülöp, 2001). Weighting of criteria is an important part of the PROMETHEE MCDA methodology (Ostovare and Shahraki, 2019) and the industrial survey used in this project seeks to strengthen this process in this project. The use of dedicated software helped with the implementation of the of the PROMETHEE methodology (Ishizaka and Nemery, 2011) and in this project ‘Visual PROMETHEE Educational Software’ was used. Each criteria requires a preference function which defines differences in pairwise evaluations, these are translated into degrees of function and are a reflection of the perception of the criteria scale by the decision maker (VPSolutions, 2013). The integrated preference function assistant in the Visual Promethee Software was utilised to determine the preference function for each criteria.

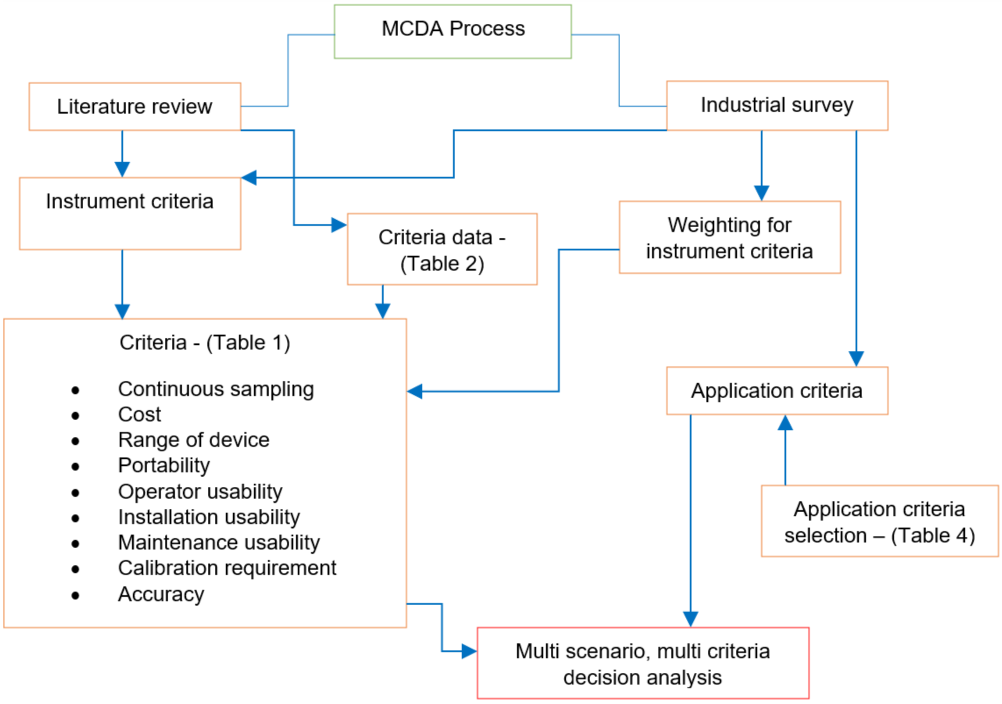

Figure 19 Multi Criteria Decision Analysis Process

The MCDA process utilised in this project for the correct selection of PM emissions measurement device is detailed in

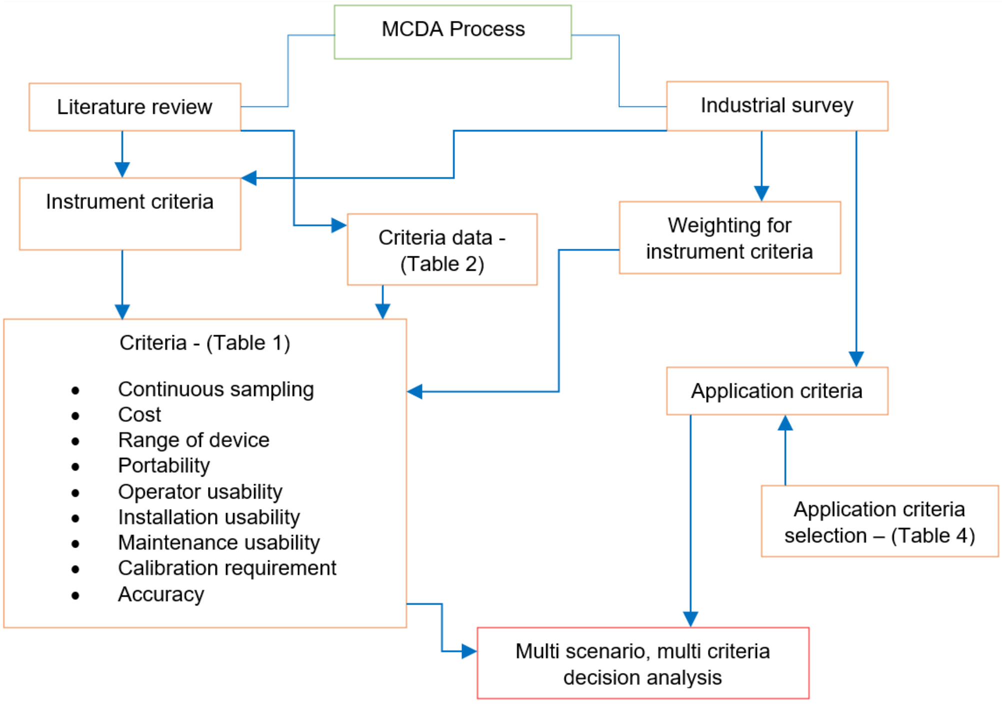
MCDA Process
Literature review
Industrial survey
Instrument criteria
Criteria data - (Table 2)
Weighting for instrument criteria
Criteria - (Table 1)
Continuous sampling
Cost
Range of device
Portability
Operator usability
Installation usability
Maintenance usability
Calibration requirement
Accuracy
Application criteria
Application criteria selection – (Table 4)
Multi scenario, multi criteria decision analysis

Figure 19, showing how the criteria, weighting and data is selected and the influence and application of the literature review and industrial survey to obtain accurate results.

The industrial survey was undertaken as a systematic method of calculating the weighting for each criteria in this project. The results from the survey were input into the weighting criteria as a percentage, taken from the importance of criteria for each participant when deciding upon a measurement device or technology to measure dust particulate emissions from stationary sources. (This survey question was asked generically, independent of the participants application or field of work). The weighting of criteria is essential to accurately represent the priorities of the decision maker.

To select the criteria to be analysed, participants in the survey were given a list of carefully selected suggestions derived from the literature review as well as an open opportunity to submit their own. The criteria required accurate data to be analysed against, this data was taken from the extensive literature review and manufactures data sheets. The requirements for each criteria are detailed in Table 2, and the scale and range used are detailed in Table 3. The Visual PROMETHEE software allows the preference for each range to be set to a maximum or a minimum depending upon the scenario and application-based criteria analysis.

MCDA results can be expressed in different ways. Partial ranking is a comparison of the leaving flow (Phi+) and the entering flow (Phi-), where Phi+ represents the technology with most positive criteria and Phi- represents the technology with least negative criteria (VPSolutions, 2013). Long (Long, 2016) explains that MCDA results are presented by means of the total function value obtained for each action. This means that actions are prioritised from the highest and lowest Phi value. Phi +1 = best solution and Phi -1 = worst solution. Complete ranking is based upon the net preference flow by combining the other preference flows in a single score. This means that all actions are compared and that the ranking will not include any incomparability.
Phi+ (φ^{+}) can be expressed as;

$$\varphi^{+}(a) = \frac{1}{n-1}\sum_{b\neq a} \pi\,(a,b) \tag{2}$$

Where φ^{+} measures how much an action a, is preferred to the other n-1 actions, being a global measurement of the strength of action a.

Phi- (φ^{-}) can be expressed as;

$$\varphi^{-}(a) = \frac{1}{n-1}\sum_{b\neq a} \pi\,(b,a) \tag{3}$$

Where φ^{-} measures how much the other n-1 actions are preferred to action a, being a global measurement of the weakness of action a.

Phi (φ) can be expressed as:

$$\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a) \tag{4}$$

Where φ considers both the strengths and weaknesses of the action into a single output.

Criteria	**Requirement**
Continuous sampling	Based upon the instrument's capability for continuous measurement according to the MCERTS requirement for continuous measurement
Cost	Based upon the capital cost of the product, not including costs of maintenance requirements
Range of device	Based upon the operating range of the product
Portability	Based upon whether the instrument is designed to be transported between applications rather than assigned to one site as a fixed installation
Operator usability	Based upon the ability for the end user to operate the instrument including operating basic functionality
Installation usability	Based upon the ease of installation for the qualified installation engineer. It should be noted that this is product, not application based

Maintenance usability	Based upon the requirements for maintenance taking into consideration maintenance frequency, work required at each interval, and therefore costs incurred for the maintenance.
Calibration requirement	Based upon the requirement for calibration for the intended device to function in its operating conditions
Accuracy	Based upon the accuracy of the device as a percentage

Table 2 Criteria Requirements for MCDA

Criteria	**Scale**	**Range**
Continuous sampling	Qualitative	Yes, no
Cost	Currency (£)	5,000 - 70,000
Range of device	Qualitative	Very high, high, medium, low, very low
Portable	Qualitative	Yes, no
Operator usability	Qualitative	Difficult, moderate, simple
Installation usability	Qualitative	Difficult, moderate, simple
Maintenance usability	Qualitative	Difficult, moderate, simple
Calibration requirement	Qualitative	Yes, no
Accuracy	Numerical	5% - 30%

Table 3 MCDA Scale and Range for each Criteria

Scenarios were used to assess the decision process from the viewpoint of different decision makers by modifying the selection of criteria to suit the requirements of the intended application. Decision makers for the purpose of this project are researchers and operators of plant who require methodology to select the most appropriate method of measurement for their intended application. The application-based criteria Table 4 was developed through the comprehensive literature review and results from the industrial survey to develop scenarios to aid a range of decision makers in changing applications. The stack diameter and concentration criteria were split into range categories; at set points where the parameters of measuring equipment characteristics change.

Scenarios for the purposes of this project are application-based criteria which represent the views of the different decision makers. Nine carefully selected applications are analysed in this project to cover a full range of applications for stationary source dust particulate measurement. Successful measurement is based upon matching measurement equipment to the required application.

	Categories		
	Application Criteria	**Range**	**Justification**
1	Stack diameter for continuous monitoring (non isokinetic)	0.3-3m	Stack diameters for stationary sources can range from 0.3m to 18m. Measurement devices have operating ranges which impacts selection. This includes continuous monitoring devices as isokinetic sampling can be undertaken over the full range of stack diameters, but addition sampling points may be required for accuracy.
2		3-6m	
3		6-18m	
4	Concentration	0-200mg/m3	Dust particulate measurement devices have detection limits and a concentration operating range, the measurement device must be selected to fit this criteria.
5		200-1000mg/m3	
6		1000-10000mg/m3	
7	Changing conditions	n.a	If the process is subject to changing fuel characteristics the PM emissions will be subject to change as a result, including particle size, composition, shape, colour, and refractive index. It is difficult to undertake accurate measurements using continuous monitoring due to the requirement of recalibration.
8	Changing velocity	n.a	Continuous monitoring in changing emissions characteristics can be difficult but some devices operate better than others.
9	Chemical analysis required	n.a	Sample analysis can only be undertaken following the collection of a sample either on a filter or similar method.

Table 4 Application Criteria and Justification

During the survey, participants were asked questions regarding the application of measurement technologies, data from these questions was used to aid selection of application-based variables. The comparison of selected technologies were eliminated in instances where not appropriate for certain applications Table 5, this allows MCDA to be undertaken on relevant technologies where suitable for the application criteria. The information in Table 5 is derived from both the literature review, industrial survey and information found in

Table 1. Beta Attenuation, Standard Reference Method and TEOM are not included for any selection of stack diameter in the application criteria, this is because all are carried out under isokinetic conditions and this application criteria relates only to non-isokinetic sampling for continuous methods, represented in Table 5 as n.a. Where a technology is suitable for the application criteria it is represented by ✓, where a technology is not suitable for the application criteria it is represented by ×.

Application Criteria	**Range**	**Ratiometric opacity**	**Standard opacity**	**Back scatter laser**	**Forward scatter laser**	**Beta attenuation**	**Standard reference method**	**Triboelectric probe**	**Electrodynamic probe**	**TEOM**
Stack diameter for continuous monitoring (non isokinetic)	0.3-3m	✓	✓	✓	✓	n.a	n.a	✓	✓	n.a
	3-8m	✓	✓	✓	✓	n.a	n.a	×	×	n.a
	8-18m	✓	✓	×	×	n.a	n.a	×	×	n.a
Concentration	0-200mg/m3	✓	✓	✓	✓	✓	✓	✓	✓	✓
	200-1000mg/m3	✓	✓	✓	×	✓	✓	✓	✓	×
	1000-10000mg/m3	×	✓	×	×	✓	✓	×	×	×
Changing conditions	n.a	×	×	×	×	✓	✓	×	×	✓
Changing velocity	n.a	✓	✓	✓	✓	✓	✓	×	×	✓

Chemical analysis required	n.a	×	×	×	×	×	✓	×	×	✓

Table 5 Application Criteria Selection

7 Results

For clarity, results are displayed visually in Figures 20 – 28, this includes both complete ranking and GAIA (Graphical Analysis for Interactive Aid) web form. These results are consolidated in Table 6, which details the best available technology to measure dust particulate emissions mass concentration for a single application.

The GAIA webs show a graphical representation of the unicriterion net flow scores for the selected technology. Conventional spiderweb graphs display the variables equally spaced around the centre of the display, with the shape being dependent upon the arbitrary order of the criteria. The GAIA web expresses similar preferences close to each other giving more meaningful visual analysis. For each dimension, the radial distance corresponds to the net flow score with -1 values drawn at the centre of the web with +1 values at the outer circle, with a polygon connecting the criteria.

Categories		
Application Criteria	**Range**	**Best available measurement technology**
Stack diameter for continuous monitoring (non isokinetic)	0.3-3m	Standard opacity, ratiometric opacity, electrodynamic probe and triboelectric probe
	3-8m	Standard opacity and ratiometric opacity
	8-18m	Standard opacity
Concentration	0-200mg/m3	Standard reference method (Ratiometric opacity, electrodynamic probe, triboelectric probe for continuous monitoring)
	200-1000mg/m3	Standard reference method (Ratiometric opacity and electrodynamic probe for continuous monitoring)
	1000-10000mg/m3	Standard reference method (Standard opacity for continuous monitoring)
Changing conditions	n.a	Standard reference method (TEOM for continuous monitoring)
Changing velocity	n.a	Standard reference method (Ratiometric opacity and standard opacity for continuous monitoring)
Chemical analysis required	n.a	Standard reference method (TEOM for continuous monitoring)

Table 6 Best Available Technique

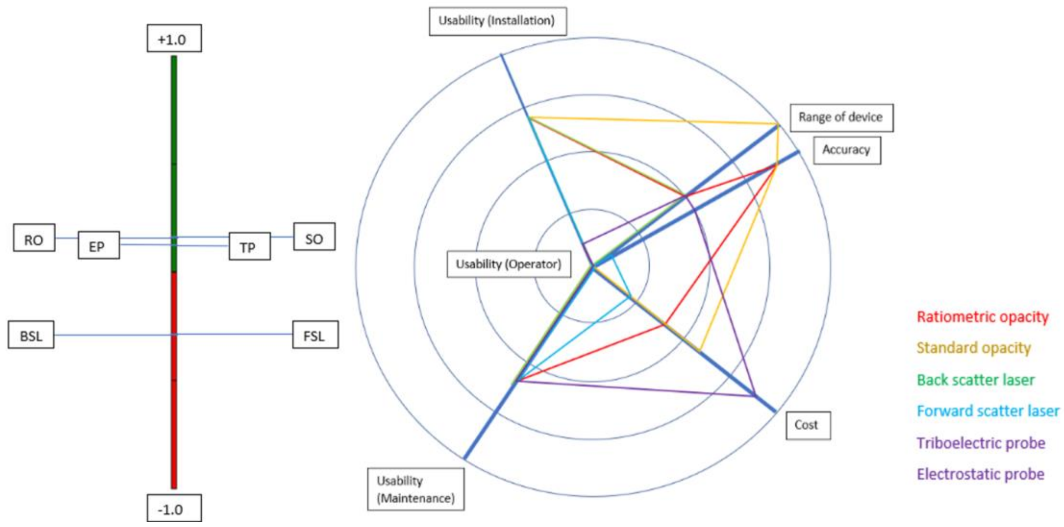

Figure 20 MCDA complete ranking results showing the best available techniques for a stack diameter of 0.3m – 3m non isokinetic

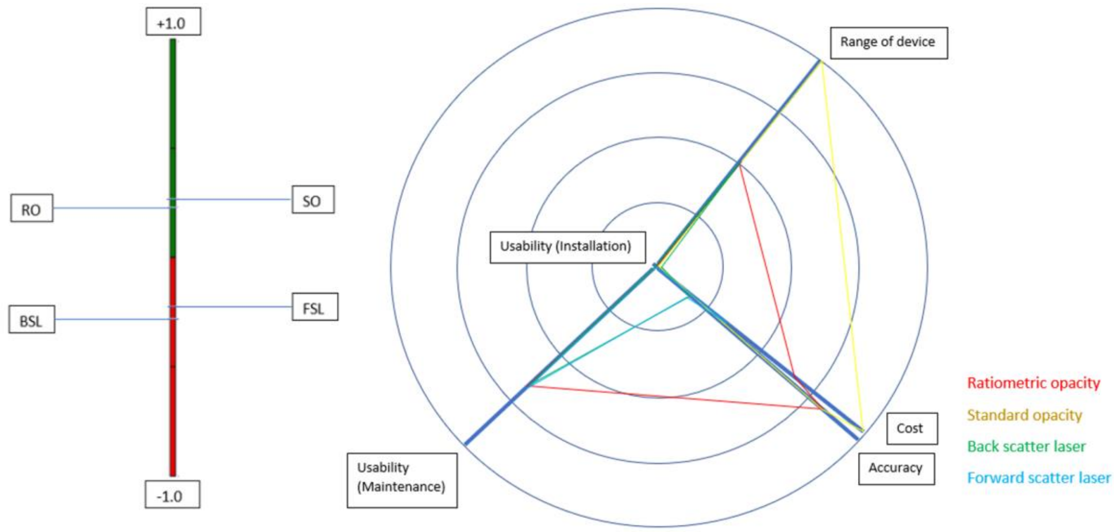

Figure 21 MCDA complete ranking results showing the best available techniques for a stack diameter of 3m – 8m non isokinetic

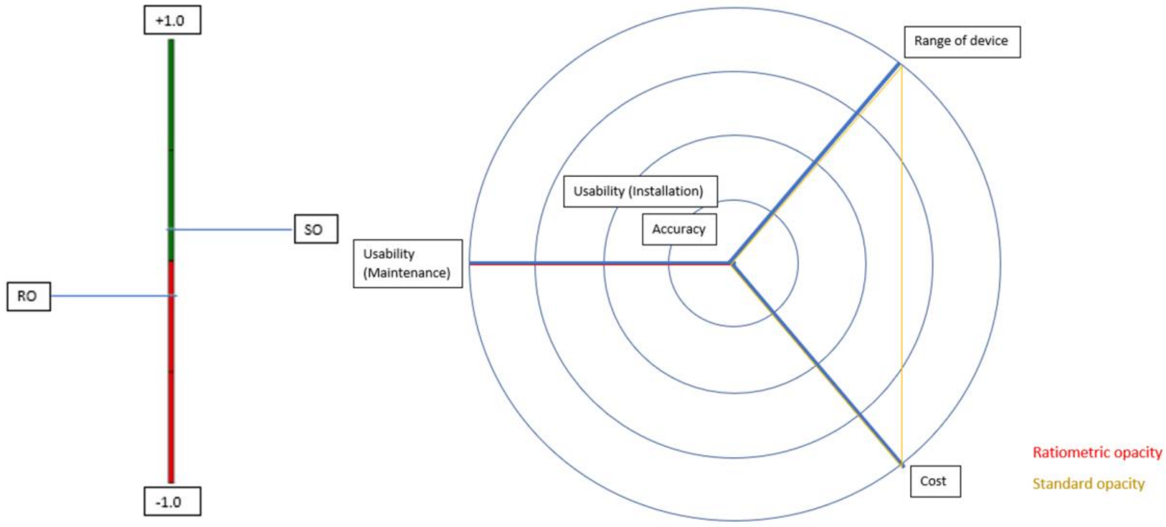

Figure 22 MCDA complete ranking results showing the best available techniques for a stack diameter of 8m – 18m non isokinetic

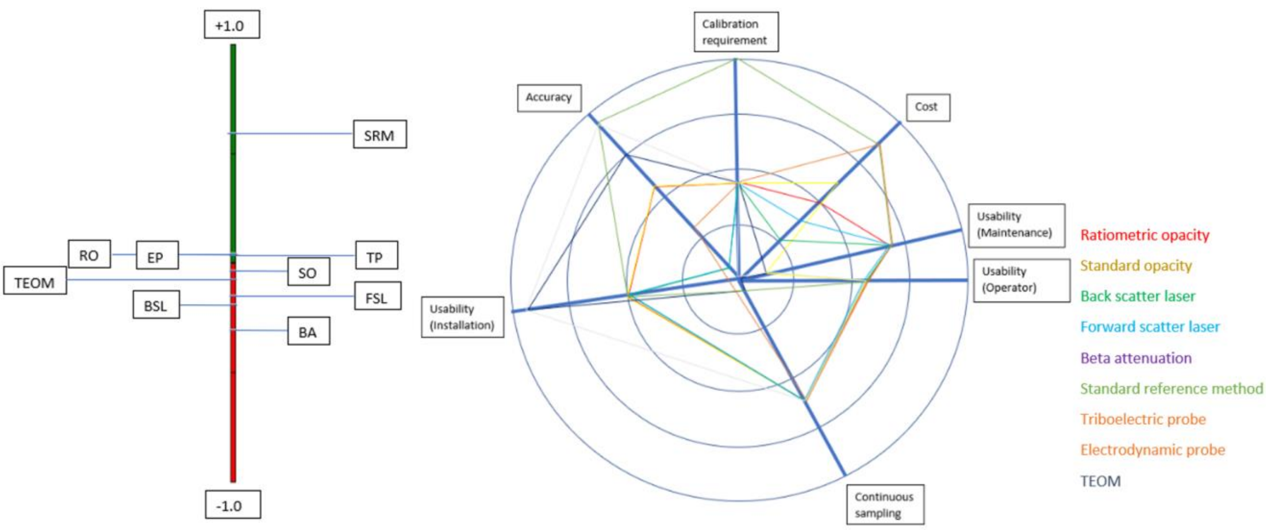

Figure 23 MCDA complete ranking results showing the best available techniques for a concentration of 0mg/m3 – 200mg/m3

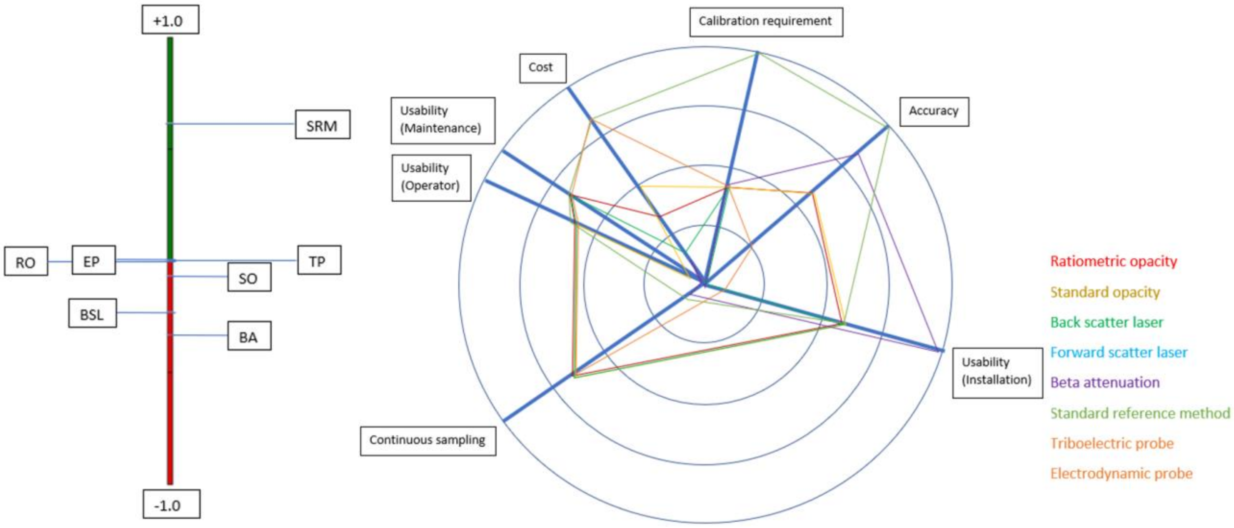

Figure 24 MCDA complete ranking results showing the best available techniques for a concentration of 200mg/m3 – 1000mg/m3

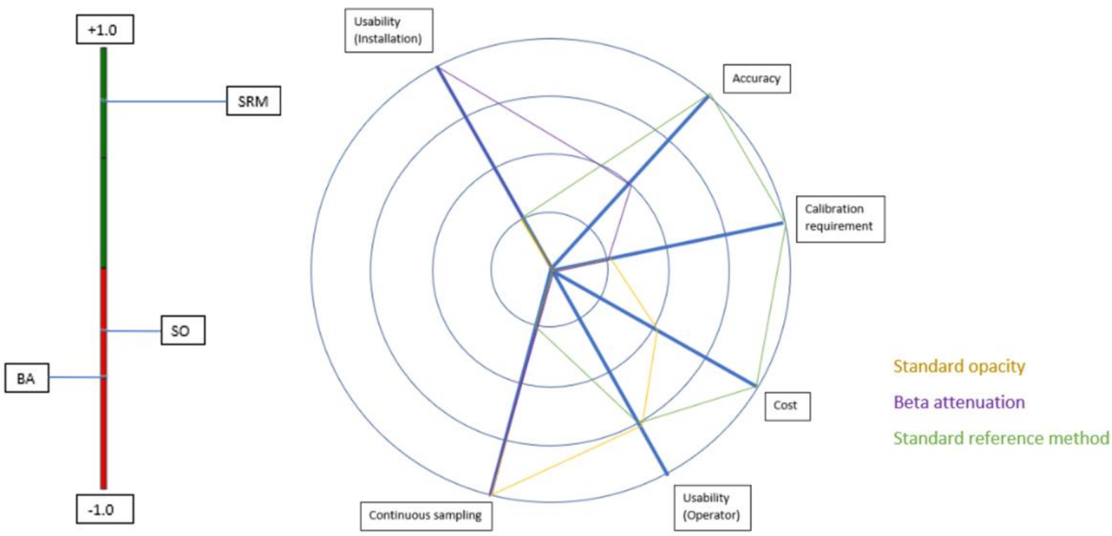

Figure 25 MCDA complete ranking results showing the best available techniques for a concentration of 1000mg/m3 – 10000mg/m3

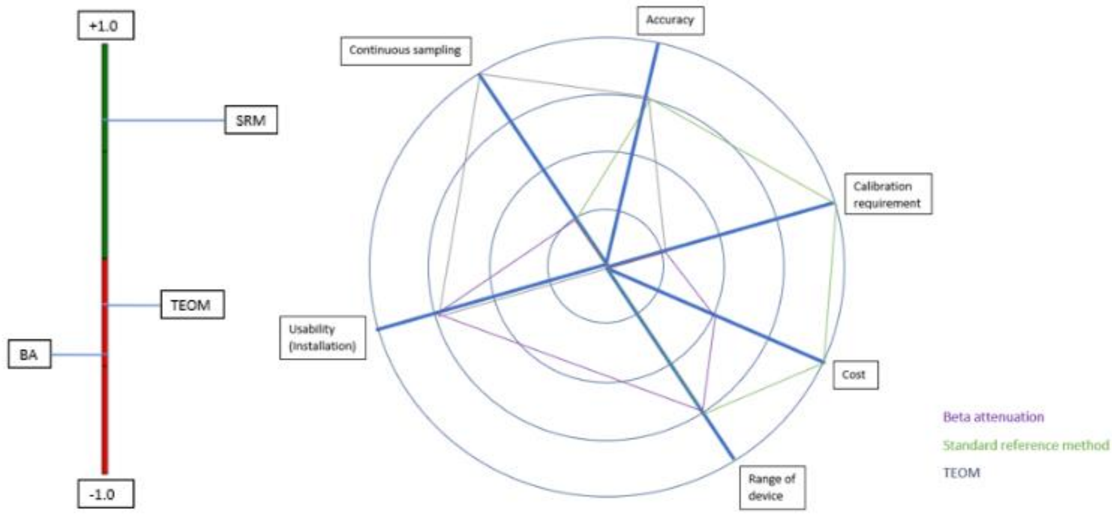

Figure 26 MCDA complete ranking results showing the best available techniques for use in changing conditions

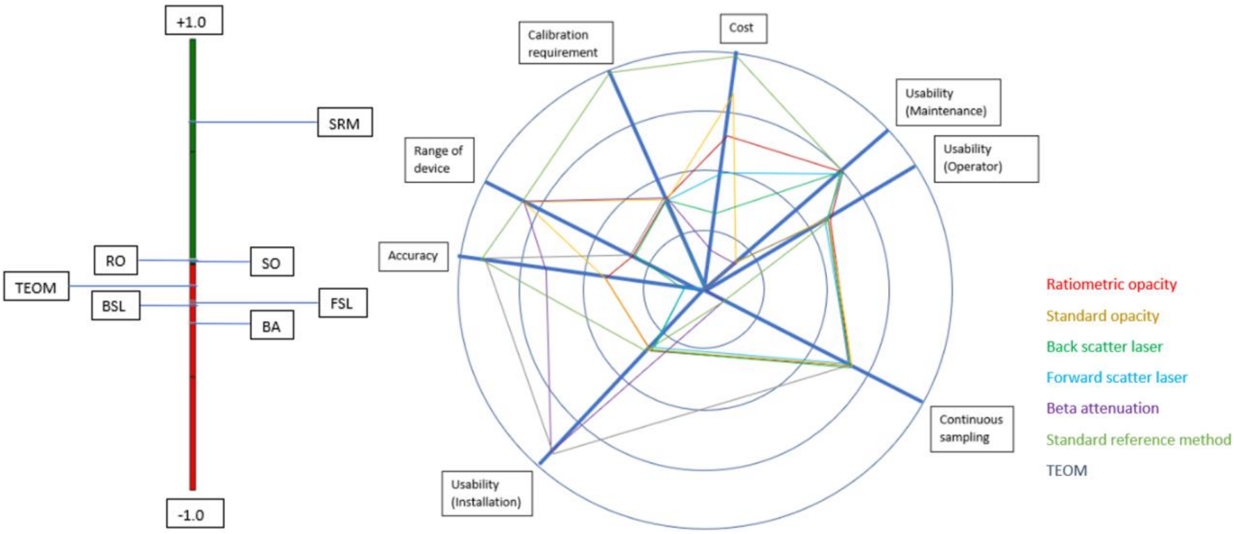

Figure 27 MCDA complete ranking results showing the best available techniques for use in changing velocity

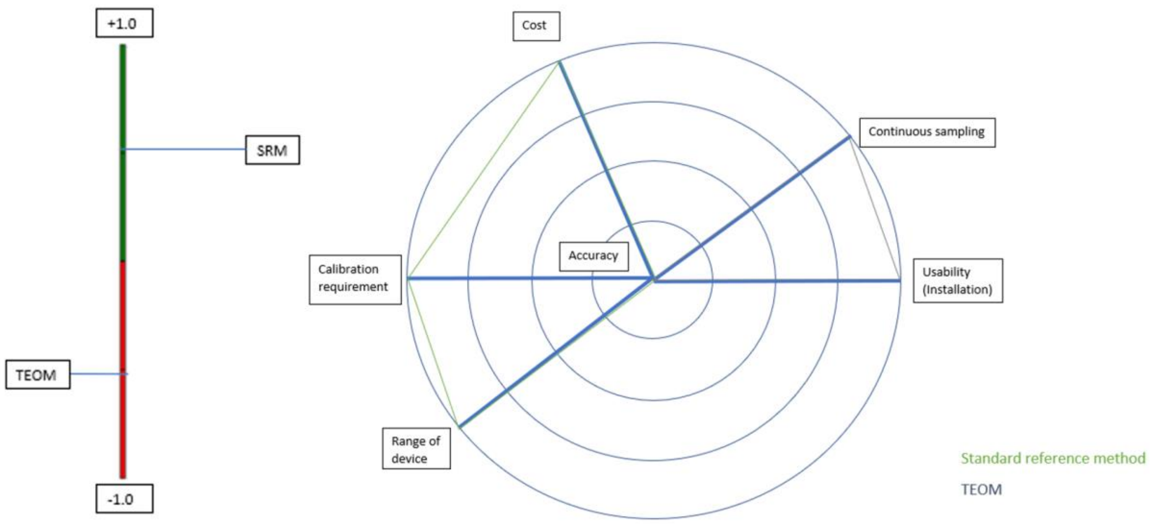

Figure 28 MCDA complete ranking results showing the best available techniques use where chemical analysis is required

Measurement technologies can be required to meet 2 application criteria. In this situation where the application criteria is required to meet two categories, Table 7 can be used as a reference to find a suitable solution. There are instances where there is currently no suitable solution to meet the application criteria, the standard reference method should always be considered when no continuous monitoring solution is possible. If there is a requirement for continuous monitoring to comply with legislation where no suitable measurement technology is available, the relevant governing body should be consulted to discuss potential solutions that satisfy legislative requirements.

For applications where isokinetic sampling is suitable, the standard reference method is always the best technique regardless of the application criteria. For this reason, other techniques have been included to show the best available technique where continuous monitoring is required. Where there is little difference between technologies, all options that are suitable have been included in the best available measurement technology. The weakness for the standard reference method is its lack of suitability where continuous monitoring is required.

There is no solution to meet the full range of criteria and it is therefore critical to match the measurement technology to the application that it is intended to avoid potential costly errors and inaccurate results. An article written by PCME (PCME Ltd, 2016) states the importance of choosing the best technology and methodology for the application of intended use. Where there are multiple options of suitable equipment, the decision maker should refer to Table 7 and any organisational criteria which may also influence choice. Where there are not any specific organisational requirements, the methodology detailed in this project and use of produced results will provide the best available technique for a range of applications.

		Stack diameter for continuous monitoring (non isokinetic)			**Concentration**			**Changing conditions**	**Changing velocity**	**Chemical analysis required**
		0.3-3m	**3-8m**	**8-18m**	**0-200mg/m3**	**200-1000mg/m3**	**1000-10000mg/m3**			
Stack diameter for continuous monitoring	**0.3-3m**	-	-	-	Ratiometric opacity, electrodynamic probe and	Ratiometric opacity and electrodynamic probe	Standard opacity	Not available	Standard opacity and	Not available

(non isokinetic)					triboelectric probe				ratiometric opacity	
	3-8m	-	-	-	Ratiometric opacity	Ratiometric opacity	Standard opacity	Not available	Standard opacity and ratiometric opacity	Not available
	8-18m	-	-	-	Not available	Not available	Standard opacity	Not available	Standard opacity	Not available
Concentration	**0-200mg/m3**	Ratiometric opacity, electrodynamic probe and triboelectric probe	Ratiometric opacity	Not available	-	-	-	Standard reference method	Ratiometric opacity	Standard reference method
	200-1000mg/m3	Ratiometric opacity and electrodynamic probe	Ratiometric opacity	Not available	-	-	-	Standard reference method	Ratiometric opacity	Standard reference method
	1000-10000mg/m3	Standard opacity	Standard opacity	Standard opacity	-	-	-	Standard reference method	Standard opacity	Standard reference method
Changing conditions		Not available	Not available	Not available	Standard reference method	Standard reference method	Standard reference method	-	Standard reference method	Standard reference method
Changing velocity		Standard opacity and ratiometric opacity	Standard opacity and ratiometric opacity	Standard opacity	Ratiometric opacity	Ratiometric opacity	Standard opacity	Standard reference method	-	Standard reference method
Chemical analysis required		Not available	Not available	Not available	Standard reference method	Standard reference method	Standard reference method	Standard reference method	Standard reference method	-

Table 7 Application Criteria Suitable for Dual Application

8 Conclusions

Due to the heightened requirements of legislation and because continuous monitoring of particulate emissions is becoming cheaper, there is a trend towards using these measurement techniques not only for particulate measurement but also process monitoring.

The problem with the calibration of automatic devices at <10mg/m^3 remains unsolved. Technology is available to measure these low concentrations of particulate but verification against a reference method is difficult with no method available capable of measuring mass directly and continuously.

Applying the incorrect measurement technique to the wrong application can have significant cost implications. This can be due to a lack of understanding regarding requirements from regulations and therefore application of wrong techniques, or a lack of understanding of the application and not knowing what emissions characteristics, are likely to be expected.

Most continuous particulate emissions monitors are sensitive to changes in particle characteristics, which becomes a problem if the application has changing emissions due to changing fuel. Each device is calibrated to its environment and a change in particulate emissions in terms of particle characteristics could render the instrument response unreliable. There are many changing process conditions such as velocity, particle size and composition that can also affect the calibration of a device, therefore the difficulty is not obtaining calibration but maintaining calibration.

Factors that can affect the accuracy of sampling include temperature difference between hot sampling gas and the pipe wall, and the surface roughness from the pipe itself or the particles. Combining all the possible factors, losses in the sampling lines of a particulate monitor can reach 69% after 0.2 seconds for PM10 although smaller particles have lower percentage losses.

There are very few technologies available to measure mass concentration continuously at low levels, the question is to be asked, however, how these devices can be verified when calibration at low levels is not possible.

MCDA analysis was used evaluate the most suitable technique to measure particulate mass concentration in mg/m^3. The results show that there is no solution that is suitable across the whole range of criteria. In applications where continuous sampling is not required the standard reference method is the best technique regardless of the application criteria. The methodology used in this project and results from the survey and MCDA can be used to aid selection of equipment for a range of applications where continuous monitoring is a requirement. The weakness for the standard reference method is its lack of suitability where continuous monitoring is required.

The analysis presented in this project is driven by the fact that there are a wide variety of stationary sources producing dust particulate emissions which can significantly vary from process to process. Operators have varying reasons to measure particulate, including satisfying legislation and industrial requirements and process control and monitoring which may influence the selection of equipment.

There is potential for further research into the technologies used to measure particulate, confirmed by 1/3 of the participants in the survey who felt that adequate technology is not yet available to measure particulate emissions, with 81% stating various problems with current equipment and methods of measurement.

Further research should include the development of a method to measure particulate matter from combustion processes accurately and reliably at low concentration down to less than 5m/m^3. Ideally the measurement process should measure dust particulate emissions directly to avoid the requirement for process calibration.

Gravimetric measurement is the most commonly used method to measure particulate, currently being used by 83% of experts in the industry. There is a requirement to use the gravimetric standard reference method to calibrate all continuous methods of measurement to give meaningful results, which suggests why this technique is most popular, although this method does have room for improvement.

The measurement of particulate mass concentration is a technically challenging field, with so many variables affecting the methodology and technology. There is no product currently available that is suitable for all applications, but with careful consideration, and the application of the methodology used throughout this project, the best available technique can be chosen for a range of applications.

9 Funding/Acknowledgements

This research is to form part of the SEND project (ref.32R16P00706) and is part-funded through the European Regional Development Fund (ERDF) as part of the England 2014 to 2020 European Structural and Investment Funds (ESIF) Growth Programme and is available to ERDF eligible companies. The project is also receiving funds from the Department for Business, Energy and Industrial Strategy (BEIS).

We would like to thank Martin McGraw and Lee Bloor of DRM Technic and Bahamin Bazooyar of Staffordshire University for their support and assistance with this project.

10 References

Apex Instruments, 2008. Isokinetic Source Sampler Method 5.

Arouca, F.O., Feitosa, N.R., Coury, J.R., 2010. Effect of Sampling in the Evaluation of Particle Size Distribution in Nanoaerosols. Powder Technol. 200, 52–59. https://doi.org/10.1016/j.powtec.2010.02.007

Averdieck, B.W., 2000. Dynamic Opacity – A New Proven Technique for Continuous Dust.

Averdieck, W., 2011. Selection of Particulate Monitors - Technical Paper.

Averdieck, W., 1994. Air Pollution ; Choosing the Right Analysis Technology 10.

Beutner, H.P., 1974. Measurement of Opacity and Particulate Emissions with an On-Stack Transmissometer. J. Air Pollut. Control Assoc. 24, 865–871. https://doi.org/10.1080/00022470.1974.10469984

Bivins, D., 2000. Current Knowledge of Particulate Matter (PM), Program Manager.

Brodny, J., Tutak, M., 2019. Analysis of the diversity in emissions of selected gaseous and particulate pollutants in the European Union countries. J. Environ. Manage. 231, 582–595. https://doi.org/10.1016/j.jenvman.2018.10.045

BSI Standards, 2017a. BS EN 13284-1 : 2017 BSI Standards Publication Stationary Source Emissions – Determination of Low Range Mass Concentration of Dust.

BSI Standards, 2017b. BS EN 13284-2 : 2017 BSI Standards Publication Stationary Source Emissions – Determination of Low Range Mass Concentration of Dust.

Buonanno, G., Ficco, G., Stabile, L., 2009. Size Distribution and Number Concentration of Particles at the Stack of a Municipal Waste Incinerator. Waste Manag. 29, 749–755. https://doi.org/10.1016/j.wasman.2008.06.029

Calcagno, J.A., 2001. Data Analysis and Correlations for the Particulate Matter Continuous Emission Monitoring System Test Program at the TSCA Incinerator.

Castellani, B., Morini, E., Filipponi, M., Nicolini, A., Palombo, M., Cotana, F., Rossi, F., 2014. Comparative Analysis of Monitoring Devices for Particulate Content in Exhaust Gases. Sustain. 6, 4287–4307. https://doi.org/10.3390/su6074287

Cemtek Environmental, Inc. Particulate Matter Monitoring Technologies and Detection Principles CEMTEK Environmental [WWW Document], 2011. URL https://slideplayer.com/slide/5264610/

Chen, A., Zu, J., Wei, P., Miao, Y., 1998. Study on Particulate Emission Monitoring by Means of Scintillation. Conf. Rec. - IEEE Instrum. Meas. Technol. Conf. 2, 1018–1022. https://doi.org/10.1109/imtc.1998.676877

Chen, D., Liu, X., Han, J., Jiang, M., Xu, Y., Xu, M., 2018. Measurements of Particulate Matter Concentration by the Light Scattering Method: Optimization of the Detection Angle. Fuel Process. Technol. 179, 124–134. https://doi.org/10.1016/j.fuproc.2018.06.016

Chung, A., Chang, D.P.Y., Kleeman, M.J., Perry, K.D., Cahill, T.A., Dutcher, D., McDougall, E.M., Stroud, K., 2001. Comparison of Real-Time Instruments Used to Monitor Airborne Particulate Matter. J. Air Waste Manag. Assoc. 51, 109–120. https://doi.org/10.1080/10473289.2001.10464254

Clean Air Instrument Rental, 2015. Method 5 Isokinetic Sample Train.

Corrigan, A.E., Becker, M.M., Neas, L.M., Cascio, W.E., Rappold, A.G., 2018. Fine particulate matters: The impact of air quality standards on cardiovascular mortality. Environ. Res. 161, 364–369. https://doi.org/10.1016/j.envres.2017.11.025

Djoumi, L., Blondeau-Patissier, V., Vanotti, M., Appert-Collin, J.-C., Thomas, D., Fertier, L., 2016. Surface Acoustic Wave Sensors for PM2.5 and PM10 Concentration. Procedia Eng. 168, 696–699. https://doi.org/10.1016/J.PROENG.2016.11.250

Eiseman, E., 1998. Monitoring for Fine Particulate Matter.

Elmes, M., Gasparon, M., 2017. Sampling and single particle analysis for the chemical characterisation of fine atmospheric particulates: A review. J. Environ. Manage. 202, 137–150. https://doi.org/10.1016/j.jenvman.2017.06.067

Eneva, 2018. BETA 5M - Beta Attenuation Particulate Monitor.

Engdahl, R.I.M.& R.B., 2012. A Survey for Improved Methods for the Measurement of Particulate Concentraion in Flowing Gas Streams. J. Air Pollut. Control Assoc. https://doi.org/10.1080/00022470.1963.10468220

Environment Agency, 2017a. Technical Guidance note - M1 Sampling Requirements for Stack Emission Monitoring.

Environment Agency, 2017b. Technical Guidance Note - M2 Monitoring of Stack Emissions to Air.

Environment Agency, 2012. Technical Guidance Note M15 - Monitoring PM 10 and PM 2.5 Environment Agency.

Favez, O., Ne Cachier, H., Sciare, J., Le Moullec, Y., 2007. Characterization and contribution to PM 2.5 of semi-volatile aerosols in Paris (France). Atmos. Environ. 41, 7969–7976. https://doi.org/10.1016/j.atmosenv.2007.09.031

Fontane, D.G., 2014. Multi-Criteria Decision Analysis Software Guide.

Fülöp, J., 2001. Introduction to Decision Making Methods. Oper. Res. 1–15. https://doi.org/10.1.1.86.6292

Ge, S., Bai, Z., Liu, W., Zhu, T., Wang, T., Qing, S., Zhang, J., 2001. Boiler Briquette Coal Versus Raw Coal: Part I - Stack Gas Emissions. J. Air Waste Manag. Assoc. 51, 524–533. https://doi.org/10.1080/10473289.2001.10464293

Giechaskiel, B., Maricq, M., Ntziachristos, L., Dardiotis, C., Wang, X., Axmann, H., Bergmann, A., Schindler, W., 2014. Review of Motor Vehicle Particulate Emissions Sampling and Measurement: From Smoke and Filter Mass to Particle Number. J. Aerosol Sci. 67, 48–86. https://doi.org/10.1016/j.jaerosci.2013.09.003

Gonnet, G., Forges, F.-B.S., 2004. Real Time Measurement Of Particulate At Low Concentration From The Emission Of Stationary Source In The Steel And Power Industries Using a TEOM™ based Emissions Monitor.

Green, D., Fuller, G.W., 2006. The Implications of Tapered Element Oscillating Microbalance (TEOM) Software Configuration on Particulate Matter Measurements in the UK and Europe. Atmos. Environ. 40, 5608–5616. https://doi.org/10.1016/j.atmosenv.2006.04.052

Gunawardena, J., Egodawatta, P., Ayoko, G.A., Goonetilleke, A., 2013. Atmospheric deposition as a source of heavy metals in urban stormwater. Atmos. Environ. 68, 235–242. https://doi.org/10.1016/j.atmosenv.2012.11.062

Hermans, C., Erickson, J., Noordewier, T., Sheldon, A., Kline, M., 2007. Collaborative environmental planning in river management: An application of multicriteria decision analysis in the White River Watershed in Vermont. J. Environ. Manage. 84, 534–546. https://doi.org/10.1016/j.jenvman.2006.07.013

Ishizaka, A., Nemery, P., 2011. Selecting the best statistical distribution with PROMETHEE and GAIA. Comput. Ind. Eng. 61, 958–969. https://doi.org/10.1016/j.cie.2011.06.008

Jahnke, J.A., 2000. Continuous Emission Monitoring.

Jones, T.L., Baxter, M.A.J., Khanduja, V., 2013. A Quick Guide to Survey Research. Ann. R. Coll. Surg. Engl. 95, 5–7. https://doi.org/10.1308/003588413X13511609956372

Kamiya, H., Hada, K., Sekizawa, T., Yamada, M., Tsukada, M., Lenggoro, W., Wada, M., Kogure, N., Yuping, Y., Szymanski, W.W., 2011. Measurement and Analysis of Fine Particulate Matters (PM10/PM2.5) and Condensable Nanoparticles Emission from Stationary Sources. WIT Trans. Ecol. Environ. 154, 71–81. https://doi.org/10.2495/CHEM110081

Kanchan, S.K., 2018. Particulate Matter CEMS.

Keller, H.R., Massart, D.L., Brans, J.P., 1991. Multicriteria decision making: A case study. Chemom. Intell. Lab. Syst. 11, 175–189. https://doi.org/10.1016/0169-7439(91)80064-W

Koehler, K.A., Peters, T.M., 2015. New Methods for Personal Exposure Monitoring for Airborne Particles. Curr. Environ. Heal. reports 2, 399–411. https://doi.org/10.1007/s40572-015-0070-z

Kuo, Y.-M., Hsu, C.-W., Chen, J.-Y., Huang, S.-H., Lee, L.-H., Chen, C.-C., 2015. Development of a Reliable and Cost-Effective Weighing Chamber for Aerosol Sample Analyses 15, 749–758. https://doi.org/10.4209/aaqr.2014.10.0260

Lee, Y.Y., Park, H., Seo, Y., Yun, J., Kwon, J., Park, K.W., Han, S.B., Oh, K.C., Jeon, J.M., Cho, K.S., 2020. Emission characteristics of particulate matter, odors, and volatile organic compounds from the grilling of pork. Environ. Res. 183, 109162. https://doi.org/10.1016/j.envres.2020.109162

Lim, M.C.H., Ayoko, G.A., Morawska, L., Ristovski, Z.D., Jayaratne, E.R., Kokot, S., 2006. A comparative study of the elemental composition of the exhaust emissions of cars powered by liquefied petroleum gas and unleaded petrol. Atmos. Environ. 40, 3111–3122. https://doi.org/10.1016/j.atmosenv.2006.01.007

Lim, M.T., Phan, A., Roddy, D., Harvey, A., 2015. Technologies for Measurement and Mitigation of Particulate Emissions from Domestic Combustion of Biomass: A Review. Renew. Sustain. Energy Rev. 49, 574–584. https://doi.org/10.1016/j.rser.2015.04.090

Liu, D., Zhang, Q., Jiang, J., Chen, D.R., 2017. Performance Calibration of Low-Cost and Portable Particular Matter (PM) Sensors. J. Aerosol Sci. 112, 1–10. https://doi.org/10.1016/j.jaerosci.2017.05.011

Liu, J., Hao, W., Liu, M., Liang, Y., He, S., Liu, J., Hao, W., Liu, M., Liang, Y., He, S., 2018. A Novel Particulate Matter 2.5 Sensor Based on Surface Acoustic Wave Technology. Appl. Sci. 8, 82. https://doi.org/10.3390/app8010082

Long, G., 2016. Coordination and Support Action (Coordinating Action) Report on the Multi-criteria Methodology, the Process and the Results of the Decision Making.

Machrafi, H., 2012. Green Energy and Technology, Green Energy and Technology. https://doi.org/10.2174/97816080528511120101

Meyer, M.B., 2004. Sampling, Real-time Monitoring and Conditioning of Air Samples for Determination of Particle Mass.

Mills, J., 1999. Development Of A Real-Time Stack Particulate Mass Monitor.

Nader, J.S., 1975. Current Technology for Continuous Monitoring of Particulate Emissions. J. Air Pollut. Control Assoc. 25, 814–821. https://doi.org/10.1080/00022470.1975.10470141

Nathalie, F., 2015. Literature Review and Practical Experiences on Continuous Dust Monitoring at Low Concentrations.

Nussbaumer, T., Czasch, C., Klippel, N., Johansson, L., Tullin, C., 2008. Particulate Emissions from Biomass Combustion in IEA Countries Survey on Measurements and Emission Factors.

O'Brien, P., 2019. Isokinetic Sampling Part 2: Isokinetic Sampling In Accordance with NEMAQA Sampling.

Oetari, P.S., Hadi, S.P., Huboyo, H.S., 2019. Trace elements in fine and coarse particles emitted from coal-fired power plants with different air pollution control systems. J. Environ. Manage. 250, 109497. https://doi.org/10.1016/j.jenvman.2019.109497

Ostovare, M., Shahraki, M.R., 2019. Evaluation of hotel websites using the multicriteria analysis of PROMETHEE and GAIA: Evidence from the five-star hotels of Mashhad. Tour. Manag. Perspect. 30, 107–116. https://doi.org/10.1016/j.tmp.2019.02.013

Patashnick, H., Rupprecht, E.G., 1991. Continuous PM-10 Measurements Ssing the Tapered Element Oscillating Microbalance. J. Air Waste Manag. Assoc. 41, 1079–1083. https://doi.org/10.1080/10473289.1991.10466903

PCME Ltd, 2019a. PCME QAL 181 Datasheet.

PCME Ltd, 2019b. PCME QAL 181 WS Datasheet.

PCME Ltd, 2019c. PCME STACK 602 Datasheet.

PCME Ltd, 2019d. PCME QAL 360 Datasheet.

PCME Ltd, 2016. Total Solution : Gas and Particulate Analysis in Cement Industry.

Ponto, J., 2015. Understanding and Evaluating Survey Research. J. Adv. Pract. Oncol. 6, 168–71.

Pope, C.A., Coleman, N., Pond, Z.A., Burnett, R.T., 2020. Fine particulate air pollution and human mortality: 25+ years of cohort studies. Environ. Res. 183, 108924. https://doi.org/10.1016/j.envres.2019.108924

ProScatter^{TM} Backscatter | PCME [WWW Document], 2019. URL https://www.pcme.com/technologies/proscatter-backscatter

Rahmat, M.F. ad, Tajdari, T., 2011. Particles Mass Flow Rate and Concentration Measurement using Electrostatic Sensor. Int. J. Smart Sens. Intell. Syst. 4, 313–324.

https://doi.org/10.21307/ijssis-2017-441

Rary, L.T.R., Bldg, N.W., Meyer-Arendt, J.R., Emmanuel, C.B., 1965. Optical Scintillation; A Survey of the Literature.

Richards, J.R., 2000. Air Pollution Training Institute (APTI) - Control of Particulate Matter Emissions.

Sabaei, D., Erkoyuncu, J., Roy, R., 2015. A review of multi-criteria decision making methods for enhanced maintenance delivery. Procedia CIRP 37, 30–35. https://doi.org/10.1016/j.procir.2015.08.086

Sanju Thomas, Farah H. Villa-López, Jan Theunis, Jan Peters, Marina Cole, and J.W.G., 2015. Particle Sensor Using Solidly Mounted Resonators. IEEE Sens. J. https://doi.org/10.1109/JSEN.2015.2512303

Sherman, L., Cantor, A., Milman, A., Kiparsky, M., 2020. Examining the complex relationship between innovation and regulation through a survey of wastewater utility managers. J. Environ. Manage. 260, 110025. https://doi.org/10.1016/j.jenvman.2019.110025

Soysal, U., Géhin, E., Algré, E., Berthelot, B., Da, G., Robine, E., 2017. Aerosol Mass Concentration Measurements: Recent Advancements of Real-Time Nano/Micro Systems. J. Aerosol Sci. 114, 42–54. https://doi.org/10.1016/j.jaerosci.2017.09.008

Stack Particulate Monitor ENVEA - BETA Attenuation [WWW Document], 2019. URL http://www.environnement-sa.com/products-page/en/stack-particulates-beta-5m-2/

Teledyne Instruments, 2003. Particulate Matter Monitor Model 360.

TEOM Technology for Particulate Matter Measurement - UK [WWW Document], 2019. URL https://www.thermofisher.com/uk/en/home/industrial/environmental/environmental-learning-center/air-quality-analysis-information/teom-technology-particulate-matter-measurement.html

Time, R., Impactor, C., On, B., Measurement, C., 2018. Real Time Cascade Impactor Based On Surface Acoustic Wave Delay Lines for PM10 and PM2.5 Mass Concentration Measurement. https://doi.org/10.3390/s18010255

Tiwary, A., Colls, J., 2010. Air pollution: Measurement, Modelling and Mitigation, Taylor and Francis Group.

US - EPA, 2017. EPA Method 5 1–41.

Vallero, D.A., 2008. Fundamentals of Air Pollution Fourth Edition.

Volker Lenz, Daniela Thrän, D.P., 2018. Methods for Measuring Emissions of Particulate Matter from Solid Biomass Combustion Biomass Energy Use.

VPSolutions, 2013. Visual PROMETHEE Operator Manual.

Wang, J.C.F., Kee, B.F., Linkins, D.W., Lynch, R.W., 1983. Real-Time Total Mass Analysis of Particulate in the Stack of an Industrial Power Plant. J. Air Pollut. Control Assoc. 33, 1172–1176. https://doi.org/10.1080/00022470.1983.10465708

Wang, J.C.F., Patashnick, H., Rupprecht, G., 1980. A New Real-Time Isokinetic Dust Mass Monitoring System. J. Air Pollut. Control Assoc. 30, 1018–1021. https://doi.org/10.1080/00022470.1980.10465140

William Averdieck, 2015. Improvements in Continuous Particulate Emission Monitoring as a Result of the Independent Verification Schemes UBA, TUV AND MCERTS.

William Averdieck, 2014. Electrodynamic Technology for Particulate Monitoring.

William Averdieck, 1997. Electrodynamic Technology Monitors Emissions with Precision.

World Health Organization, 2015. Ambient (Outdoor) Air Quality and Health. World Heal. Organ. 1–8.

Yan, Y., Ma, J., 2000. Measurement of Particulate Velocity Under Stack-Flow Conditions. Meas. Sci. Technol. 11, 59–65. https://doi.org/10.1088/0957-0233/11/1/309

Yong Yan, 2005. Continuous Measurement of Particulate Emissions. IEEE Instrum. Meas. Mag. 8, 35–39. https://doi.org/10.1109/mim.2005.1518620

Zhu, R., Zhang, Y., Yuan, Y., Li, S., 2018. Deposition Loss of Particles in the Sampling Lines of Continuous Emission Monitoring System (CEMS) in Coal-Fired Power Plants. Aerosol Air Qual. Res. 18, 1483–1492. https://doi.org/10.4209/aaqr.2017.11.0523