Chapter 15
Air Monitoring

As mentioned in Chap. 1, there are two approaches to implement the air emission standards. One is best technology approach and another is air emission monitoring. Air emission monitoring from a source is also referred to as source test, which provides technical information for judging the relative importance of a given source contribution of pollutants. It is also a measure to determine whether a pollution control device installed is working effectively as expected. Sometimes, the analysis of sources of air emissions, such as boilers, incinerators, and diesel engines, also provides complementary information to their energy efficiencies. After all, energy production and the environmental pollution are closely related. The source test results are used in the design and tuning of control methods as well as a legal tool in the case of a violation of an air pollution control regulation.

It is unusual to take only one sample and make a claim because it is solely by luck one can achieve this goal. Actual engineering applications are much more complicated. In order to obtain this accurate information, multiple samples and measurements must be taken followed by engineering statistical analysis to quantify both emission rates and their uncertainties.

Reference Methods have been developed by government agencies or professional societies to guide these practices. In the United States, for example, all reference methods for stationary source tests are available to the public for free on the web site of Emission Measurement Center (http://www.epa.gov/ttn/emc/). These Reference Methods specify the procedures and certified equipment for measuring the constituents of emissions. They also describe the principles, applicability, and presentation of the test results.

15.1 Flow Rate and Velocity Measurement

There are a number of flow rate measurement technologies and related instruments; one of them is Pitot tube, named after Henri Pitot in 1732. It is widely used in engineering practices because of its simplicity, accuracy, reliability, and cost-effectiveness.

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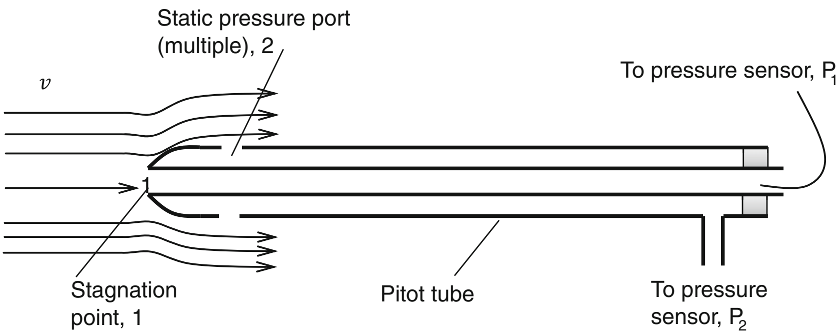


Fig. 15.1 *L-shaped* Pitot tube

A standard Pitot tube is an L-shaped tube depicted in Fig. 15.1. When it is located in a pipe, streamlines connect the stagnation point and the multiple static taps, which are small holes evenly distributed along the circumference of the outer tube.

Applying Bernoulli's Equation (Eq. 2.74) to the stagnation point, where $u_1 = 0$, and the static taps, we can get

$$\Delta P = P_1 - P_2 = \frac{1}{2}\rho u_2^2 \tag{15.1}$$

and the fluid speed near the static taps is

$$u = u_2 = \left(\frac{2\Delta P}{\rho}\right)^{1/2} \tag{15.2}$$

where ΔP is the reading from the differential manometer at the other end of the Pitot tube. The corresponding air volume flow rate is calculated as

$$Q = Au. \tag{15.3}$$

15.2 Source Sampling

As introduced above, a representative sample is the key to the accurate measurement of air emissions from a source. Different source test methods have been developed for a variety of realistic environments. In the USA, for example, most states rely upon US EPA Reference Methods, Methods 1–8, for characterization of the gas flow and specific air pollutants from a stationary source. They are listed as follows:

Method 1:	Sample and velocity transverse for stationary sources
Method 2:	Determination of stack gas velocity and volumetric flow rates using Type S Pitot tube,
Method 3:	Gas analysis for the determination of dry molecular weight
Method 4:	Characterizing moisture content in stack gases
Method 5:	Determination of particulate matter emission from stationary sources
Method 6:	Determination of sulfur dioxide emissions from stationary sources
Method 7:	Determination of nitrogen oxide emissions from stationary sources
Method 8:	Determination of sulfuric acids and sulfur dioxide emissions from stationary sources

These methods set the foundation for other subsequent methods. The first four methods are supportive but necessary in that they provide information for other methods or the calculation of the results. The other four are for the determination of different air emissions as explicitly indicated by their titles. Method 1 is the first step for any source testing; it is concerned with assessing the suitability of the sampling site and determining the sampling points. The principles behind these Methods will be introduced shortly.

These sampling methods are similar to each other with exchangeable equipment; this similarity allows a single sampling train to be used by multiple methods by adding or removing impingers, filters, or other appropriate devices. For example, Method 5 is typically combined with Methods 2, 3, and 4 in order to determine gas velocity, molecular weight and moisture content, which are required to calculate a particulate emission rate. Method 5 and 8 can also be combined by adding additional impingers and an in-stack filter to the probe on the Method 5 sampling train.

Figure 15.2 shows a schematic diagram of a typical sampling train for Method 5, which is available online (e.g., http://www.epa.gov for free use). A typical sampling train starts with a heated probe, or a hollow glass tube that is inserted into the stack or duct and the last component is a pump drawing gases through the system. Other pieces of equipment include filters and impingers to capture different air pollutants of concern. A gas meter measures the flow rate of sampled gas and the stack gas velocity at the sampling point is measured using a Pitot tube with a manometer (Sect. 15.1). Finally, the sample exhaust is discharged into the atmosphere through the orifice, which is used for sample train flow adjustments at the by-pass valve.

15.2.1 Isokinetic Sampling

Isokinetic sampling has to be executed for particulate matter related source tests. Under isokinetic condition, the gas velocity entering the probe is the same as the bulk air velocity.

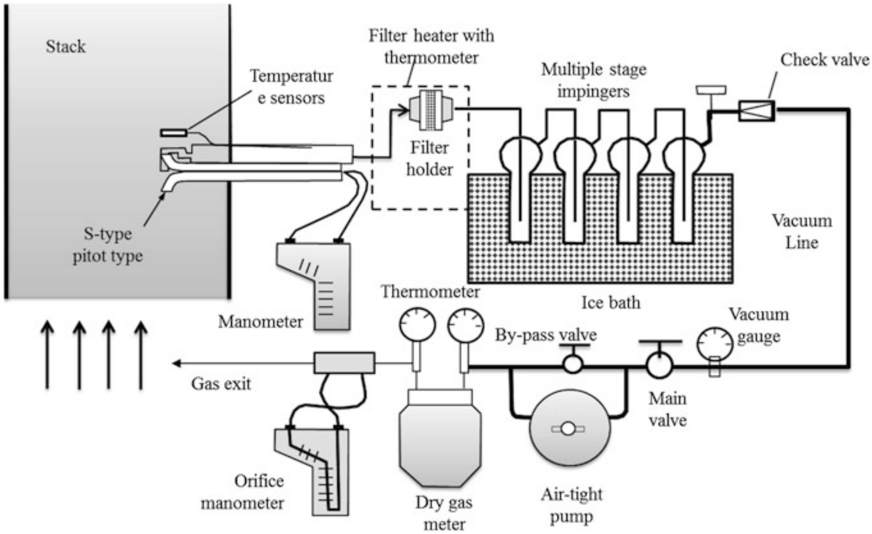


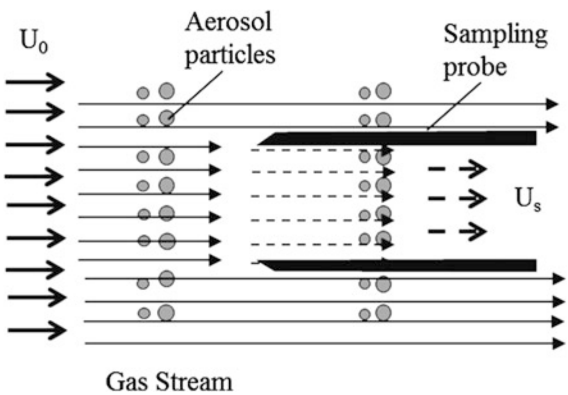
Fig. 15.2 Sampling train for particulate matter (US EPA Method 5)

$$U_s = U_0 \tag{15.4}$$

Under isokinetic condition, as illustrated in Fig. 15.3, particles of different sizes follow the air stream and enter the probe as if there were no probe in the area.

Sampling with velocity U_s lower or higher than the gas stream velocity U_0 is called anisokinetic sampling. They are depicted in Fig. 15.4. Anisokinetic sampling results in errors in the particulate concentration measurements. When the sampling velocity is greater than the gas stream velocity ($U_s > U_0$), it is called over isokinetic; gas from regions not directly in front of it is drawn into the probe and the converging streamlines results in loss by separation of large particles. These particles are

Fig. 15.3 Isokinetic sampling



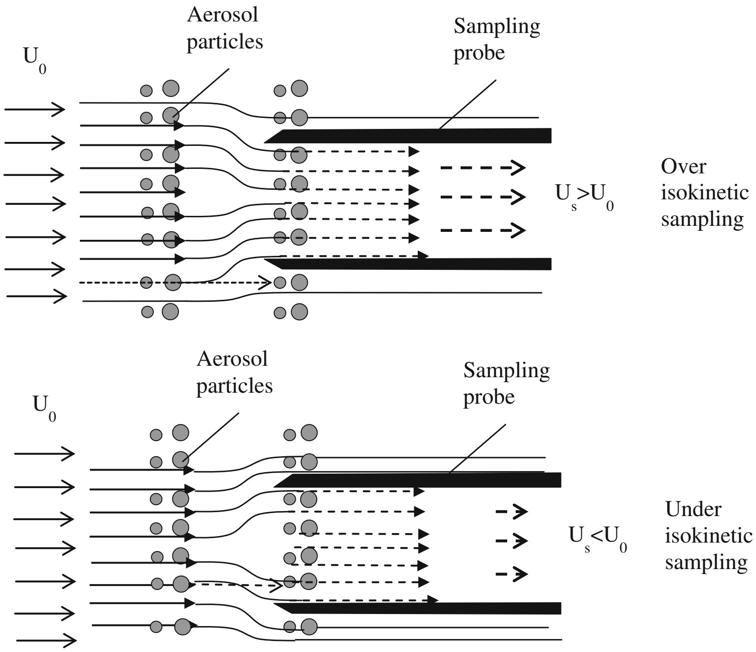


Fig. 15.4 Anisokinetic sampling by velocity mismatch

excluded from the sample, and consequently this practice underestimates the concentrations of large particles in the gas stream. On the other hand, small particles tend to follow the gas streamlines, and their concentrations are over estimated. Overall, over isokinetic sampling results in the underestimation of the particulate mass concentration because large particles contribute much more to the mass than smaller ones. An alternative way to understand this process is that the particulate matter is entering the sampling probe diluted by over sampling of the gas into the probe.

When the sampling velocity is less than that of the gas stream, it results in under isokinetic sampling. Because of the lower sampling velocity, some gas bypasses the probe as if it were an obstruction. As a result, a smaller volume of gas is taken into the probe. However, the large particles in the gas stream still enter the probe due to their great inertia and the diverging gas streamline. The sample is also biased with overestimated large particle concentrations.

The sampling efficiency is a ratio of the sampled concentration to that in the bulk air stream. That is,

$$\eta_s = C_s/C_0 \tag{15.5}$$

In reality, it is very challenging to achieve 100 % isokinetic sampling and most reference methods consider an isokinetic sampling efficiency in the range of ±10 %

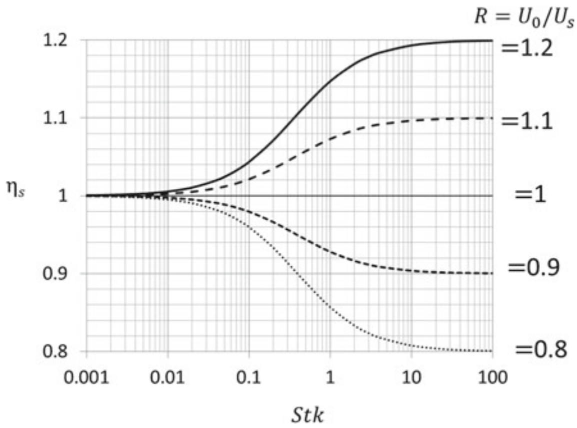


Fig. 15.5 Sampling efficiency η_s versus R and Stk (velocity mismatch only)

acceptable. Note that isokinetic sampling is not necessary if only gaseous pollutants are of concern.

The sampling efficiency can be calculated in terms of particle *Stokes* number, the sampling velocity and the bulk air velocity.

$$\eta_s = 1 + (R - 1)\beta(\mathrm{Stk}, R) \tag{15.6}$$

$$\text{where} \quad \mathrm{R} = \mathrm{U_0/U_s} \tag{15.7}$$

and $\beta(\mathrm{Stk}, R)$ is a function of particle Stokes number and the velocity ratio. Belyaev and Levin [1] gave a practical formula that matched the experimental data corresponding to 0.18 < Stk < 6.0 and 0.16 < R< 5.5.

$$\beta(\mathrm{Stk}, R) = 1 - \frac{1}{1 + (2 + 0.617/R)\mathrm{Stk}} \tag{15.8}$$

Figure 15.5 is produced using Eq. (15.8), the calculation results show that $\eta_s \to 1$ when Stk $\to 0.01$ and $\eta_s \to R$ when Stk $\to \infty$. $\eta_s \approx 1 \pm$ 0.05 for Stk < 0.1 and η_s becomes little dependent on Stk. When Stk > 10 the equation can be practically simplified as $\eta_s = R$

$$\begin{aligned} \eta_s &\approx 1 \quad \text{for Stk} < 0.1 \\ \eta_s &\approx R \quad \text{for Stk} > 10 \end{aligned} \tag{15.9}$$

15.2.2 *Effect of Misalignment*

The preceding analysis is based on the assumption that the sampling velocity and the bulk air velocity have the same direction. In practice, it implies the perfect

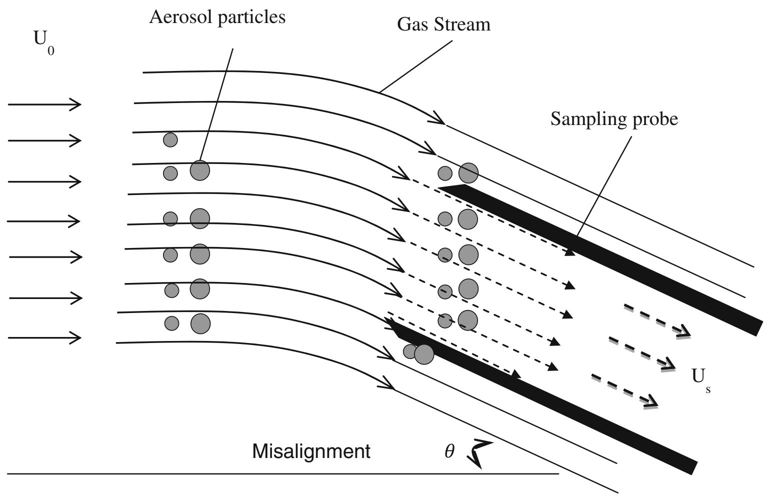


Fig. 15.6 Misalignment in air sampling

alignment between the sampling probe and the bulk air flow direction. As seen in Fig. 15.6, misalignment between the probe and the bulk air velocity may also lead to sampling error.

Empirical equations were given by Durham and Lundgren [5] to quantify the misalignment effect for anisokinetic sampling as follows:

$$\eta_s = 1 + (\cos\theta - 1)\beta'(\mathrm{Stk}', \theta) \quad \text{for } \mathrm{R} = 1 \tag{15.10}$$

where $\beta'(\mathrm{Stk}', \theta)$ is a function of Stokes number and the angle of misalignment,

$$\beta'(\mathrm{Stk}', \theta) = 1 - \frac{1}{1 + 0.55\ \mathrm{Stk}'\exp(0.25\ \mathrm{Stk}')} \tag{15.11}$$

and

$$\mathrm{Stk}' = \mathrm{Stk} \times \exp(0.022\theta) \quad \text{for } 0 \le \theta < \pi/2 \tag{15.12}$$

Since $\cos\theta < 1$, this equation indicates that misalignment of the probe always results in the underestimation of the particle concentration.

Figure 15.7 is produced using Eq. (15.10) above for $R = 1$. It shows that the sampling efficiency is always less than unity when $\theta \neq 0$; again, the most dramatic change in sampling efficiency corresponds to the range of $0.1 < \mathrm{Stk} < 10$.

When there are both misalignment and mismatch in air velocities, Eq. (15.13) can be used for estimating the sampling efficiency.

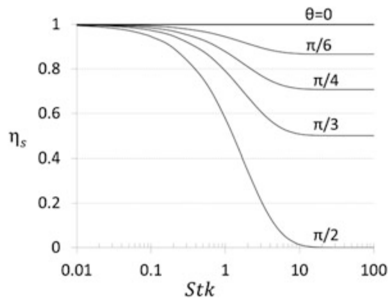


Fig. 15.7 Misalignment sampling efficiency when $R = 1$

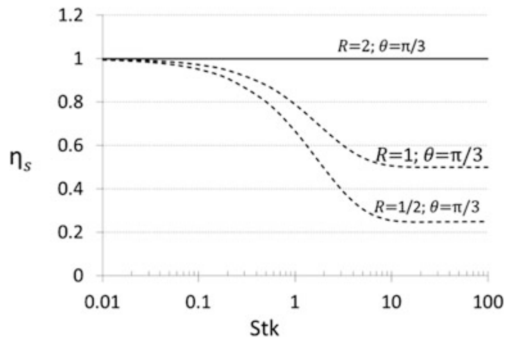


Fig. 15.8 Misalignment sampling efficiency when $R \neq 1$ $(\boldsymbol{\theta} = \frac{\pi}{3})$

$$\eta_s = 1 + (R\cos\theta - 1)\beta'(\mathrm{Stk}', \theta)\frac{\beta(\mathrm{Stk}', R)}{\beta(\mathrm{Stk}', R = 1)} \tag{15.13}$$

However, it is useful to realize that the sampling efficiency is always 1 when $R\cos\theta = 1$, regardless of the value of $\beta'(\mathrm{Stk}', \theta)\beta(\mathrm{Stk}', R)/\beta(\mathrm{Stk}', R = 1)$. This simple relationship is of practical use; the error introduced by misalignment can be compensated by increasing R value to such a level as $R = 1/\cos\theta$. This concept is also illustrated by a sample calculation of the sampling efficiency shown in Fig. 15.8, which shows that $\eta_s = 1$ when $R = 2$ and $\cos\theta = 1/2$.

15.2.3 Multiple Sampling Locations

Air in the stack is not as uniform as described in the theoretical analysis above; it is turbulent and is not characterized as parabolic velocity profile. Therefore, it is very difficult for a practitioner to determine one sampling point that can represent the average velocity of the entire stack. As a rule of thumb, air sampling in duct should be conducted at multiple points at the transverse plan perpendicular to the duct axis. A common practice in determining the sampling points is the *equal area method*.

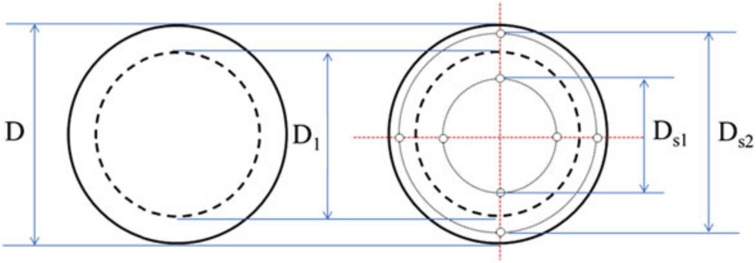


Fig. 15.9 Equal area method for a circular duct (*Left* equal area determination. *Right* sampling point determination)

Sampling points are distributed over equal areas of the cross section of the stack or duct.

A typical stack is circular. Consider a circular stack with an inner diameter of D, its cross section area can be easily determined as $A = \pi D^2/4$. If samples are to be taken, for whatever reasons, from two equal areas as shown in Fig. 15.9, the area of the inner circle (dashed line) is $A/2$. In this case, $\pi D_1^2/4 = A/2 = \pi D^2/8$ and $D_1 = D/\sqrt{2}$. However, the sampling points are NOT to be located on the thick dashed circle defined by D_1. Rather there will be eight sampling points evenly distributed on two other circles indicated by the dotted lines defined by D_{s1} and D_{s2} in Fig. 15.9. These dotted lines divide the inner circle and the *O*-ring into equal areas again. Then four evenly distributed sampling points on each dotted line are determined finally.

A reader may have noticed that the total stack area was actually divided into four equal ones by the dashed circle and two dotted circles. The ultimate goal of this practice is to determine the sampling points, which is defined by the imaginary sampling circles (dotted ones). A fast approach to this can bypass the step for determining the diameters of the circles (dashed lines). For the above practice, the stack is first divided into four instead of two equal areas, then the sampling points are located every other circles starting from the innermost.

Despite the tedious work, one can determine the corresponding sampling points for any stack sampling following the same principles introduce above. Consider a general case where the stack with an inner diameter of D and an area of A is to be divided into n equal annular areas (with diameters of D_i) and the corresponding $4n$ sampling points are determined as follows. In order to determine the sampling points without calculating the n equal areas, treat it as if the total area were to be divided into $2 \times n$ equal annular areas, then the diameter ith circle ($D_{si)}$ counting from the inner-most outward is defined by

$$D_{si}^2 = \frac{i}{2n} D^2 \qquad (i = 1, 3, \ldots 2n - 1) \tag{15.14}$$

On each sampling circle, there are four sampling points evenly distributed.

Similarly, the circles that divide the total area into n equal areas can be determined with i being even numbers, although they are of no practical use.

$$D_i = D\sqrt{i/_{2n}} \quad \text{where } i = 2, 4\ldots 2\text{n} \tag{15.15}$$

Example 15.1: Sampling location in stack

A stack with an inner diameter of 1.2 m is subject to source emission tests. Determine the sampling points by dividing the stack area into three equal sub-areas.

Solution

In this problem, $n = 3$ and $D = 1.2$ m are given. The sampling points are on the circles with diameters of $D_{si} = D\sqrt{i/_{2n}}$ where $i = 1, 3$ and 5

$$D_{s1} = 1.2 \times \sqrt{1/_6} = 0.4899(m)$$
$$D_{s2} = 1.2 \times \sqrt{3/_6} = 0.8485(m)$$
$$D_{s3} = 1.2 \times \sqrt{5/_6} = 1.0954(m)$$

These sampling points are depicted in Fig. 15.10, where readers can determine the equal area circle D_i by using Eq. (15.15).

In addition, samples should be taken at each of the 4n sampling points for equal duration, typically being an hour or so. For statistical analysis of the data, at least three replicates are recommended for each sample. This means at least $3 \times 4 \times n$ samples are taken for one complete test. Usually averaged results are reported with standard deviation to quantify the variations at the corresponding sampling points. As a result, source tests are time-consuming and a complete stack test may last for many hours to days.

In a real source test, the stack cross section area is often divided into more than two equal areas. The number of points is determined following local standards. In general, more sampling points are needed if particulate matter is of interest. Less sampling points are required for gaseous pollutants because the gases in typical stacks are well mixed by turbulence.

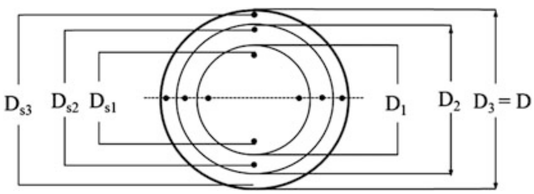


Fig. 15.10 Sampling points determined by equal area method for a circular duct

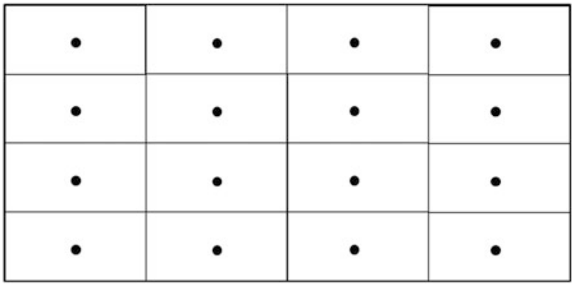


Fig. 15.11 Equal area method for a rectangular duct

Equal area method is also applicable to rectangular duct, where the determination of the sampling points is much simple. The duct perimeter is first divided into a number of girds and the sampling points are chosen at the center of each grid (Fig. 15.11). The more sampling points the more representative samples can be obtained. However, one has to compromise for time and costs.

15.3 Collection of Air Pollutant Samples

After sampled stack gas is extracted from the bulk air stream into the probe nozzle, this air sample is further drawn through a sampling train or a series of leak-proof equipment components configured to capture different air pollutants of concern. As seen in Fig. 15.2 (Method 5), water vapor and condensable are best captured by condensation or bubbling the sample gas through chilled impingers, which are sealed glass vessels. Liquid reagents may be added into the impingers to absorb some gases. Solids are likely captured on heated filters, which are connected to the probe with interconnecting glassware. Solids can also be captured by liquids in impingers.

The mass of the target air pollutant separated from the sample gas can be determined by the weights before and after sampling. Filters are weighed and reagent volumes in the impingers are measured prior to use. After each run, the content of each sampling train component is carefully recovered to a sealed vessel followed by weighing the solid loaded filters or liquids from the impingers. For some tests, the samples collected may be evaluated in a laboratory using scientific equipment.

15.4 Data Analysis and Reporting

Regardless of the end use of the data, the immediate objective of source tests is to obtain reliable and representative information of the air emissions and the rates of emissions into the atmosphere.

In general, air emission monitoring is completed by gas sampling followed by gas characterization. In addition, the properties of total gas flow from the source must also be determined accurately before calculating the corresponding air emission rates. If a gas sample with a sampling flow rate of Q_s is taken from a continuous emission source with a total flow rate of Q, typical value of Q_s is much less than Q, $Q_s \ll Q$. Characterization of the sample leads to the concentration of certain air pollutant in the sample as C_s. If this sample can be used to represent the total gas, one can claim that the concentration of the corresponding air pollutant in the main stream C_0 is the same as c_s.

Now consider a simplified case as follows. The total gas flow rate discharged from a stack to the atmosphere is Q (m^3/s), and a sample is taken with a volume flow rate of Q_s (m^3/s) for a period of time, t(s). Analysis of this sample, either in situ or in a laboratory setting, shows that the mass of air pollutant of interest is m (kg). With this information, one can calculate the mass concentration of the air pollutant in the sample $c = m/Q_s t$ (kg/m^3). If the sample is representative, it can be used to represent the concentration of the air pollutant in the stack: $C = c$. Then the mass flow rate, $\dot{m}$, of this air pollutant in the stack is determined as

$$\dot{m} = \frac{Qm}{Q_s t}(\mathrm{kg/s}) \tag{15.16}$$

The emission rate of the air pollutants can be calculated with the data obtained from the samples. However, the samples taken from different stacks are different in temperature, pressure, and moisture contents. The calculated results shall be corrected to a standard temperature and pressure and expressed on a dry basis. This standardized measure allows the source test results under different conditions to be comparable to regulatory standards or the results of other similar tests.

A common standard for emission test report is to correct the concentrations against 50 % excess air, 7 or 12 % of CO_2, or 7 % of O_2. Take 12 % of CO_2 as an example, the calculated emission rate is converted using the equation that follows. Actual procedure is much more complex, and readers are encouraged to seek local guidelines for more information.

$$C_{\mathrm{std}(12\,\%\,\mathrm{CO_2})} = C_s \times \frac{12\,\%}{100\,\% \times y_{\mathrm{CO_2}}} \tag{15.17}$$

where y_{CO_2} is the mole fraction of CO_2 in the stack gas measured (e.g., following US EPA Method 3).

15.5 Continuous Emission Monitoring and Opacity Measurement

Manual source test is a time-consuming and labor-intensive process, and there has been a growing interest in a more efficient, automatic approach. Advances in instrumental analyzers have enabled continuous emission monitoring (CEM) with modern instruments that can quickly identify many gas compounds at very low concentrations. CEM also allows monitoring of peak emissions.

There are many types of CEM instruments and systems for continuous monitoring of air emissions from stationary sources. They can be classified into extractive and In situ systems. Extractive systems can be further categorized as either dilution or direct. In situ analyzers directly measure source-level concentrations by changing the original gas properties by removal of particulate or interfering vapors or gases.

There are two types of in situ analyzers: path and point measurements. Either single or double path CEM instruments perform measurement across the entire duct or stack at certain elevation, whereas point measurement is completed by a sensor at a specific point or over a path of only a few centimeters distance. Typical in situ CEM systems can tolerate harsh environment at most locations and require fewer accessories such as probe heaters, gas conditioning systems, tubing and pumps than their extractive predecessors [7].

The 1970s saw advancements in German optical systems, which have shown great promise for measuring gas opacity, an indicator of the air emission rate [7]. The opacity of the stack gas is a function of light transmission through the plume and is determined by

$$OP = (1 - I/I_0) \times 100 \tag{15.18}$$

where OP = percent opacity, I = light flux leaving the plume, and I_0 = incident light flux.

Opacity is more lenient than the corresponding mass emission standards. The USEPA developed Method 9 to quantify the opacities of the plumes emitted from stationary point sources (http://www.epa.gov/ttn/emc/promgate/m-09.pdf). Recently, Du et al. [3] reported a method to quantify the plume opacity by digital photography and Du et al. [4] published a paper for fugitive fume detection by opacity.

Most air pollutants can now be continuously monitored by different instruments. The selection of the instruments is important to the design of the monitoring system. The choice of instrumentation for an air monitoring depends on type of pollutants and expected concentrations, accuracy required by local air quality standards, budget and personnel, etc. In the USA, CEM is required by the Clean Air Act Amendments to monitor SO_2, NO_x, CO, CO_2, opacity, total hydrocarbons, and total reduced sulfur (TRS). All the instruments are required for calibration before being used on site.

15.6 Ambient Air Quality Monitoring

Ambient air quality monitoring data is used to determine local air quality index and the levels of air pollution in the region, to establish and evaluate air pollution control measures, and to evaluate air dispersion models or some of their parameters. Sometimes it is also used to warn the citizens when the air pollution is hazardous.

Ambient air quality monitoring network in most regions employs continuous monitoring of outdoor air quality. These networks measure the amount of gaseous air pollutants and particulate matter at multiple locations to produce statistically correct data.

Like air emission monitoring systems, there are two types of ambient air quality monitoring systems: integrated and continuous monitoring systems. In integrated monitoring, samples are collected using standard devices over a certain time interval. The samples collected are analyzed in a laboratory.

A continuous air quality monitoring system constitutes both air sampling and pollutant characterization devices in one system. Samples are taken and analyzed continuously. Air pollutant concentrations are nearly instantaneously displayed or continuously recorded by a data logging mechanism. The system can also be programmed to take samples and display results over certain interval, say every 10 min or 2 h. The intervals set by the operator should follow the guideline set in the corresponding air quality standards. The data can also be sent to a central location for further analysis via wired or wireless network. On the other hand, this type of system requires sophisticated instruments and well-trained professionals to operate and to maintain the system.

An air quality monitoring network can also be mobile. Mobile air quality monitoring networks are set in trailers, automobiles, or other mobile units. They take samples and display data on schedule among selected locations. Consequently, data are collected in time sequence. The mobile air quality monitoring and sampling features its flexibility in air quality measurements and it provides a much higher resolution in the geographical variations if the air monitoring practice lasts long enough to generate meaningful data.

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