Comparative analysis of systems and methods for monitoring particulate pollution

A.I. Riabous, K.Z. Biliatdinov, V.A. Lepikhova

***Abstract* — Determination of the concentration and dispersed composition of particulate matter pollution is one of the tasks to ensure occupational safety in industry and construction. This review includes the most relevant and applied methods for monitoring the concentration of particulate air pollution.**

The methods are reviewed according to the following algorithm. First, there is a brief description of the method operation, highlighting its main idea. After that, a theoretical justification of the method with the basic formulas is given. The next step is to describe a typical monitoring system using this method, highlighting the key elements. After that, the dust measurement process is described step by step. In conclusion, the effectiveness of each method is described, including the scope of its application, accuracy, key differences from other methods and the main disadvantages or features that require some special attention.

The following five methods are considered: (1) beta-attenuation method, (2) laser scattering method, (3) method that uses Tapered Element Oscillating Microbalance (TEOM), (4) acoustic method based on the theory of ultrasonic attenuation, (5) acoustic method based on the principles of acoustic emission.

Monitoring systems based on these methods are used to determine dust concentrations in industries, construction, mines and other occupational safety tasks.

However, in the dust monitoring task the method based on the principles of acoustic emission is of interest. This method determines the concentration of dust, as well as its dispersed composition in real time. Since the other methods considered do not provide analysis of dust dispersed composition along with concentration, the acoustic emission-based method deserves further development and practical implementation.

***Key words* — air pollution, beta-attenuation method, information and expert systems, laser scattering method, monitoring, particulate matter, spectral acoustic method.**

I. INTRODUCTION

Air pollution adversely affects the environment and poses a danger to the health of human. One form of pollution is particulate matter (PM) represented as dust or suspended solids. There are respirable (PM_{10}), fine ($PM_{2.5}$), and ultrafine (PM_1) sized particles which cause illnesses ranging from allergic reactions and skin diseases to cancer, pneumoconiosis and other long-term health issues [1-2].

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Biliatdinov K.Z. – D.Sc. (Technology), Ph.D., Associate Professor, «ITMO University» (email: k74b@mail.ru).
Riabous A.I. – graduate student, «ITMO University» (email: erdandrey@yandex.ru).
Lepikhova V.A. – Ph.D., Associate Professor, Platov South-Russian State Polytechnic University (NPI) (email: odejnaya@rambler.ru).

Particulate pollution can be caused by natural reasons and household activities; however, construction and industry are among the primary sources of this type of pollution [3]. There are multiple approaches to reducing the harmful effect of pollution including wet methods and local exhaust ventilation for air pollution [4]. The choice and effectiveness of the methods used to reduce pollution depend on the concentration and dispersed composition of the dust. Thus, one of the tasks related to particulate pollution is to monitor the level and composition of hazardous pollutants in air flows.

To accomplish this task in industry and construction, monitoring systems are required to determine the composition and concentration of particulate pollution. Methods used can be classified into two big groups, one of them implying releasing the dispersed phase from aerosol, and the other one without this phase.

The former group involves methods based on obtaining a dust sample from the air and its further analysis using microscopy. This approach provides accurate results, but has a notable drawback – it is time-consuming and does not provide real-time information [5].

Methods for determining the composition of dust in real time imply using monitoring systems. In a most simplified form, a monitoring system consists of some sensors, a receiving device, a base station where the collected information is processed, a database with a database management system (DBMS) and some tools which establish communication with users [6-12]. Although monitoring system structures have some components in common, the methods used in a monitoring system vary from one system to another.

Optical methods are based on measurements of laser scattering. Depending on the size and concentration of particles, the emitted laser beam is scattered with different intensities, which can provide conclusions about the size and concentration of dust. This method produces highly accurate results in real time; however, it requires costly equipment and trained personnel [13].

The acoustic method of measuring dust concentration is based on measuring the parameters of the acoustic signal in the presence of dust particles in the working gap between the sound source and the receiver. The amount of sound energy loss due to the presence of suspended solids is proportional to the volume concentration of dust. The disadvantages of the method include a complex hardware design, as a result of which it has not found commercial application [14].

Another approach to determining the composition of dust is spectral acoustic methods. This method is based on the phenomenon of acoustic emission that occurs when the particles of a dispersed stream collide with each other and the environment. The signal received is recorded and decomposed into elementary components. Each particle fraction forms its own unique frequency spectrum which allows determining the concentration and composition of dust [15, 16].

Thus the purpose of this research is to review the most applicable real time methods for determination of dust concentration and its fractional composition, particle sizing and concentration. The review is conducted according to criteria such as the principles of operation of the method, the level of complexity and application of the monitoring systems, their cost and specificity in maintenance, accuracy and time required to obtain results.

The collected information allows assessing the current state of the dust measurement field and grounds the relevance and the rationale for further development of monitoring systems using the spectral acoustic method.

II. Review of methods

The following methods are considered:

1. beta-attenuation method
2. laser scattering method
3. method that uses Tapered Element Oscillating Microbalance (TEOM)
4. acoustic method based on the theory of ultrasonic attenuation
5. acoustic method based on the principles of acoustic emission.

For readers' convenience, all methods are considered according to the same scheme. The subtitle with the name of the method is followed by a brief description of its key idea. The following is a description of the theoretical justification of the principles of its work with the introduction of basic formulas. The next step is to describe a typical monitoring system using this method, highlighting the key elements. After that, the dust measurement process is described step by step. In conclusion, the effectiveness of each method is described, including the scope of its application, accuracy, key differences from other methods and the main disadvantages or features that require some special attention.

A. Beta-attenuation method

The beta-attenuation method is focused on exponential dependency between the attenuation of beta radiation flow and mass of studied matter. The chemical composition, density, optical properties of this matter almost do not affect mentioned dependency. This dependency can be mathematically presented as:

$$I = I_0 * e^{\mu_m * x} \quad (1),$$

where I and I_0 are the beta counts with and without an absorbing matter, μ_m is the mass absorption coefficient and x is the thickness of the absorber, usually given in mg/dm^2 with the actual thickness multiplied by the density. For low energy beta emitters, the mass absorption coefficient is almost independent of the chemical composition or the physical characteristics of the absorber [17].

A beta-emitting radioactive source is used to produce a constant beta particle flux. The most commonly used and commercially available radioactive sources are Carbon-14 (C-14), Cesium-137 (Cs-137), Strontium-90 (Sr-90) and Promethium-147 (Pm-147).

The choice of a specific radioactive source in the beta-attenuation method depends on the required energy range of beta particles, half-life, availability, cost, and the specific application of the method [18].

The method involves the following steps:

At the first step, the air containing particulate matter is drawn through a filter. The particles are deposited on a filter, loading it. Then beta particles emitted from the source pass through the loaded filter. The presence of particulate matter on the filter causes attenuation of the beta particles. The beta particles that pass through the filter are detected on the other side. The degree of attenuation is related to the mass concentration of the particulate matter on the filter. At the final stage the received data is used to calculate the particulate mass concentration and provide real-time measurement.

This method is sensitive to even small changes in particulate mass, allowing for accurate measurements. As mentioned above, the remaining parameters of the test substance do not significantly affect the result, which allows using this method in various fields from environmental monitoring to applications in coal mines and industries. Beta-attenuation method provides mostly PM_{10} measurement results but some solutions also provide $PM_{2.5}$ measurement [17, 18].

However, the method has some limitations in its application. Weather conditions, especially high humidity, affect the accuracy of measurements and lead to errors. Because radioactive materials are used in this method, more stringent maintenance requirements are imposed on monitoring systems based on this method. This fact also increases the cost of equipment in comparison with monitoring systems based on other methods.

B. Laser scattering method

Laser scattering method is based on Mie scattering theory. This theory provides an understanding of how light interacts with particles that are comparable in size to the wavelength of the incident light.

Mie scattering theory takes into account the size, shape, and refractive index of the scattering particles, as well as the wavelength of the incident light and scattering angle. It provides a solution to Maxwell's equations, which describe the behavior of electromagnetic waves, for the specific case of spherical particles. According to the Mie scattering theory, the scattered light intensity at point p from the scatterer r can be written as follows:

$$I_{sca} = I_0 g \frac{\lambda^2}{8\pi^2 r^2} g I(\theta, \phi) \quad (2)$$

$$I(\theta, \phi) = |S_1(\theta)|^2 sin^2\phi + |S_2(\theta)|^2 cos^2\phi \quad (3)$$

where I_{sca} stands for the scattered light intensity, I_0 is the incident light intensity, λ is the wavelength of the light wave, θ is the scattering angle, φ is the polarization angle of the polarized light, and $S_1(\theta)$ and $S_2(\theta)$ are two amplitude functions

$$S_1(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \pi_n + b_n \tau_n] \quad (4)$$

$$S_2(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \tau_n + b_n \pi_n] \quad (5),$$

where a_n and b_n are Mie coefficients; τ_n and π_n are Legendre polynomials that are only related to the scattering angle θ; a_n and b_n can be written as follows:

$$a_n = \frac{\phi_n(a)\phi'_n(ma) - m\phi'_n(a)\phi_n(ma)}{\varepsilon_n(a)\phi'_n(ma) - m\varepsilon'_n(a)\phi_n(ma)} \quad (6)$$

$$b_n = \frac{m\phi_n(a)\phi'_n(ma) - \phi'_n(a)\phi_n(ma)}{m\varepsilon_n(a)\phi'_n(ma) - \varepsilon'_n(a)\phi_n(ma)} \quad (7),$$

where $\phi_n(a)$ and $\varepsilon_n(a)$ are Bessel functions; a denotes the dimensionless diameter and m the refractive index of the scattered particles relative to the surrounding media [19,20].

Monitoring systems based on laser scattering method may differ in the equipment used and have improvements to perform specific tasks; however, they generally contain an optical path system, a gas circuit system and an analysis and processing system. The optical path system includes a laser source, lenses, the aperture and photoelectric sensors and allows measurement process. The gas circuit system includes a heating pipe, a gas chamber, a pressure sensor, an air pump and a filter. This system creates the analyzing particulate matter flow. The processing part consists of sensor sending circuits, the main control circuit, the analyzing and output programs [21].

The laser source emits a beam of light, which is typically in the visible or near-infrared range. The laser beam is collimated to ensure a uniform beam diameter. The laser beam is directed into the measurement chamber or the sampling area, where it encounters the dust particles present in the air. The measurement area is often designed to minimize any losses due to the reflection or absorption of the laser light. The scattered light from the particles is collected using a lens or other optical elements and directed towards a detector. The detector converts the scattered light into electrical signals. The electrical signals from the detector are amplified, filtered, and processed to extract the relevant information. The scattered light intensity is analyzed to determine the concentration of dust particles in the air. The dust concentration value is displayed on a screen or output as a digital signal, allowing for real-time monitoring or data logging. The output can be expressed in milligrams per cubic meter (mg/m³) or micrograms per cubic meter (μg/m³), depending on the specific application requirements.

Monitoring systems based on laser-scattering method are widely used in industrial, environmental, and occupational health to monitor and control the dust levels. This method allows both PM_{10} and $PM_{2.5}$ particulate matter measurements.

While widely used and effective in many applications, laser-scattering method has some drawbacks. This method is more accurate for measuring larger particles, while smaller particles may not scatter enough light to be accurately detected. This can result in underestimating the concentration of smaller particles in the air.

The laser scattering method assumes that all particles have similar optical properties and scatter light in a consistent manner. However, different types of particles, such as those with irregular shapes or varying refractive indices, may scatter light differently. This can lead to inaccuracies in measurement, and makes the described method less effective when working with complex dust suspensions. These limitations prevent accurate fractional composition of dust using laser scattering method.

C. *Tapered Element Oscillating Microbalance (TEOM)*

Tapered Element Oscillating Microbalance (TEOM) method is based on measuring the change in oscillation frequency of a tapered filter element as it accumulates particulate matter.

The oscillating tapered tube with the filter on its free end can be considered a simple harmonic oscillator. Thus, it can be presented in the form of an equation including the frequency of oscillation, the restoring force constant and the mass:

$$\omega = 2\pi f = \sqrt{k/m} \quad (8),$$

where f is the natural frequency, k is the restoring force constant and m is the oscillating mass. Otherwise, it can be written as:

$f^2 = K_0/m$, where $K_0 = K/4\pi^2$ and $m = m_F + m_0 + \delta m$

In this case, m is the sum of the values, where (m_F) is the filter mass, (m_0) is the effective oscillating mass of the tapered element, and (δm) is the mass of the substance under study. After a series of arguments described in detail in [22], the following expression is obtained for calculating the filter loading mass:

$$\delta m = K_0(1/f_f^2 - 1/f_i^2), \quad (9),$$

where f_i is the initial frequency for the microbalance and f_f is the frequency after getting an unknown loading mass.

This equation is fundamental to the evaluation of the mass uptake, which is the basis for the tapered element oscillating microbalance method.

The TEOM ambient particulate monitor consists of two main components: the TEOM sensor unit and the TEOM control unit. The control unit includes the hardware and the software for data processing, air flow control electronics and display. The sensor unit, on the other hand, consists of the sample inlet and the TEOM microbalance. The TEOM microbalance is the central component of the system, responsible for precise measurement of particulate mass. The filter and the air flow path are connected with the microbalance.

The process of determining the dust concentration using this method includes the following steps. The tapered exchangeable filter cartridge is set into oscillation at a specific frequency. The air containing particulate matter is drawn through the filter. The feedback electronics ensure that the tapered tube oscillates, while the frequency counter in the control unit accurately measures the frequency of oscillation. As particulate matter accumulates on the filter, the frequency of the system changes. This frequency data is then sent to a microprocessor for evaluation. Thus, particulate matter concentration is obtained by analyzing the relationship between the frequency and the mass loading on the filter.

The described method has found wide application in coal mines as a part of personal dust monitoring devices. It provides accurate detection of respirable (PM_{10}) and fine ($PM_{2.5}$) particulate matter.

TEOM has one noteworthy feature among continuous ambient particulate monitoring methods. It measures the mass collected on its sample filter while other methods determine particulate mass using indirect measurements. This fact allows the TEOM method to provide high accuracy measurements of dust concentration, while other methods require some specific calibration depending on the place and the measured matter [23].

On the other hand, this accuracy in measurements has its own drawbacks. The TEOM method is highly sensitive to mechanical noise and dramatic temperature fluctuations. In addition, high humidity can change the particle mass, which requires the device to be equipped with a dehumidifier and humidity sensors.

D. Acoustic method based on the theory of ultrasonic attenuation

This method involves the scattering of sound waves by dust particles. When a sound wave passes through a dusty air medium, it interacts with the particles, causing scattering and attenuation of the wave. The extent of scattering and attenuation is directly proportional to the concentration of dust particles present.

The acoustic theory proves that the sound attenuates exponentially with the change in distance, and the relationship between the plane wave and the propagation distance can be expressed as follow:

$$P_x = P_0 e^{-ax} \quad (10),$$

where P_0 is the initial sound intensity of the sound source, P_x is the intensity of the sound at a distance of x from the sound source. a is the attenuation coefficient.

The equation mentioned is applicable for a homogeneous medium, while in the multiphase mixture the sound intensity depends on the sound absorption characteristics of dust particles as well as on their concentration. In that case the particle concentration and the attenuation of the initial acoustic signal are related by the following expressions:

$$\left(\frac{\beta}{k_c}\right)^2 = 1 + \frac{3\varphi}{jk_cR^3}\sum_{n=0}^{\infty} 2n + 1)A_n \quad (11)$$

$$\beta = \frac{\omega}{c_s(\omega)} + ia_s(\omega) \quad (12)$$

From this it follows that:

$$a = -\frac{3\varphi}{2k_c^2R^3}\sum_{n=0}^{\infty}(2n + 1)Re(A_n), \quad (13)$$

where R is the particle radius. φ is the particle concentration [24].

The monitoring system typically consists of a source of ultrasonic emission, the air flow supply system, which contains the investigated dust, the sensors, which receive attenuated signal, a signal processing unit, and a data analysis component.

To measure the dust concentration using acoustic signals, a device capable of generating sound waves is placed in the air flow. Sound waves are emitted from the source and propagated through the air containing the dust particles. The sound waves then encounter the dust particles, leading to scattering and attenuation of the sound waves. The acoustic signals that pass through the dust-laden medium are received by a sensitive receiver. Analyzing the changes in the received signal determines the concentration of dust particles in the air [14].

The benefits of the dust concentration measurement method based on acoustic signals include its non-intrusiveness, real-time detection capabilities, and the ability to measure a wide range of particle sizes. Nevertheless, achieving accurate measurements with ultrasonic attenuation-based systems requires careful calibration, accounting for transducer characteristics, environmental conditions and the type of dust under study.

E. Acoustic method based on the principles of acoustic emission

This method is based on the analysis of the acoustic emission phenomenon that occurs when particles of a dispersed stream collide with each other and the environment. The produced signal is recorded by piezoelectric sensors, amplified and converted into digital form with the analog-to-digital converter. The received signal enters the system for processing, where it is decomposed into elementary components.

This means that the read signal is represented as a temporary sequence of pulses and, after processing, represents the Fourier frequency spectrum. In turn, the spectrum consists of several sub spectrums, the exact number of which depends on the dispersed composition of the dust. From each of subspectrum the fundamental and timbre frequencies are obtained. These frequencies are used to determine the size and concentration of dust fractions [25].

The fundamental and timbre frequencies of each subspectrum are determined in four steps.

1. First of all, according to the formula, with rounding up to integers, the multiplicity factors of the harmonics included in the subspectrum (14) are determined:

$$\frac{\phi_{um}}{\phi_{u1}} = \nu_i \approx k_i, \quad (14)$$

where ϕ_{um} is the adjusted frequency of the u-th experiment for the m-th harmonic; ϕ_{u1} is the corrected fundamental frequency in the u-th duplicate experiment; ν_i – approximate values of multiplicity factors; k_i – quantized integer values of multiplicity factors of timbre harmonics of the processed subspectrum.

2. The expected frequency $\phi^{\circ}{}_{u1}$ (of the first level of accuracy) of the fundamental harmonic for the analyzed subspectrum is found by formula (15):

$$\phi^{\circ}{}_{u1} = \frac{\phi_{um}}{k_i} \quad (15)$$

3. Next, the confidence frequency (of the second level of accuracy) of the fundamental harmonic of the subspectrum (16) is determined:

$$\phi^{\circ\circ}{}_{u1} = \frac{\sum_1^g \phi^{\circ}{}_{u1}}{g}, \quad (16)$$

where g is the number of harmonics included in the subspectrum.

4. And as a result, the final subspectrum vector for the selected fraction is obtained by calculating the frequency of all significant higher harmonics of the subspectrum (17):

$$\phi^{\circ\circ}{}_{u1}k_i = \phi^{\circ\circ}{}_{um} \quad (17)$$

All other subspectrum for fractions that may be present in real dust mixtures are found similarly [26].

The application of the method is divided into two tasks. The first one is a series of calibration experiments on specially prepared samples where the size and weight of particles are known. The result of such experiments makes it possible to form a database of the main harmonics of the spectrum for each dust according to the dispersed composition. This is done in the laboratory.

And, accordingly, the inverse task is to isolate monofractional subspectrum from the dust mixture and identify the composition of impurities using the data obtained at the first stage. This task is of practical importance and applied in production.

This method requires precise mathematical transformations and calculations. In addition, for full-fledged use, it requires the preliminary formation of a database of reference harmonics.

Despite these disadvantages in its application, this method has one feature that distinguishes it favorably from the other methods described in the article. The use of the spectral acoustic method allows not only to obtain information about the concentration of dust in the air, but also to determine the dispersed composition of dust under study.

III. Discussion

To our knowledge this review includes the most relevant and applied methods for monitoring the concentration of particulate air pollution. Most of the methods considered are based on some kind of emission (beta radiation, laser and ultrasound) and taking into account the difference between the initial signal and the signal after passing through the dust stream. [13, 14, 17, 18] A fundamentally different approach to solving the problem is demonstrated in the method called TEOM. It is based on the principle of measuring the change in oscillation frequency of a tapered filter element as it accumulates particulate matter [22].

These methods are well studied, and monitoring systems based on them are used to determine dust concentrations in industries, construction, mines and other occupational safety tasks [1-3].

Another aspect of dust monitoring is determination of the fractional composition of dust. It is usually performed by obtaining a dust sample from the air with further analysis by microscopic, sieve or sedimentometric method. This approach is accurate, but time-consuming and does not provide real-time information [5].

Unfortunately, the considered methods with real-time measurements do not allow performing the task of determining the dispersed composition of dust, due to the principles of their operation.

In this situation the method based on the principles of acoustic emission is of interest. The principle of its operation is the decomposition of the acoustic signal from the dust mixture with subsequent analysis of the subspectrum. This approach makes it possible to determine not only the concentration but also the dispersed composition of dust. This means that using this method allows solving two tasks at once and getting real-time monitoring results.

Thus, this method deserves more attention, which is planned to be done in subsequent research.

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