Caspian Journal of Environmental Sciences

Online ISSN: 1735-3866
Print ISSN: 1735-3033

Physical modeling of various processes in development of the system for monitoring the concentration of suspended particles in the air

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ABSTRACT

The paper shows the need to develop a system for monitoring the concentration of suspended particles in the atmosphere, ensuring industrial safety at enterprises, facilities and in rooms with high dust content. The main possible consumers of this system are presented. Different measuring techniques of suspended particles and their fractions in the air are described, their advantages and weaknesses are mentioned. The technical requirements for the installation are noted. Discrete measurements via gravimetric method are depicted. Methods used and technical appearance of the installation are pictured. The composition, structure and operational principle of the installation are described. Attention is paid to the calculation, mathematical modeling and development of the analyzer optical scheme.

Keywords: suspended particles, maximum permissible concentration, gravimetric method, Navier–Stokes differential equations, Mie scattering, physical modelling.
Article type: Research Article.

INTRODUCTION

Human activity is not unnoticed by the environment. Various types of mechanical, biological, chemical and other pollutants are the result of industrialization and commercial production. In this regard, the issue of environmental safety is acute in the modern world. Therefore, scientific research that will be useful to monitor the degree of anthropogenic environmental pollution are particularly relevant. One of the most common air pollutants in megalopolises, manufacturing centers and cities located near hazardous industrial facilities are suspended particles (hereinafter referred to as SPs). SPs have a negative impact on the human body, and its degree depends on their concentration, chemical and granulometric composition, causes diseases of the pulmonary system, oncological diseases, allergic reactions, and also creates uncomfortable living conditions. In accordance with sanitary and epidemiological norms and regulations, there are three main types of SPs by particle size-total dust, which includes particles of all sizes (TSP), fraction with SPs' size of less than 10 microns (PM10), fraction with an SPs' size of less than 2.5 microns (PM2.5). The negative impact of SPs on the human body is greater, the smaller their size is. This is due to the fact that smaller fractions of SPs penetrate deeper into the human lung system and have a more pronounced toxic effect on tissues and organs. Regulatory documents establish two types of SPs content values – one-time and average daily that are determined by sampling time. It is not greater than 20 minutes for one-time measurements, and not less than 24 hours for average daily measurements. Table 1 shows the mass concentrations of the maximum permissible one-time and average daily concentration for various types of SPs. According to long-term observations of the Russian Federal Service for Hydrometeorology and Environmental Monitoring, the content of SPs in the atmospheric air reaches the maximum permissible value at certain times of day or in certain

Caspian Journal of Environmental Sciences, Vol. 20 No. 1 pp. 165-170 Received: Aug. 17, 2021 Revised: Sep. 30, 2021 Accepted: Dec. 17, 2021
DOI: 10.22124/CJES.2022.5412

Publisher: University of Guilan, Iran

seasons in almost all cities of the country, and in the most polluted cities significant exceedances of one-time maximum permissible concentration (MPC) are frequently observed. Now the SPs content measurement in the atmospheric air is carried out in the mode of one-time measurements using gravimetric method that does not provide the possibility of fixing the rapidly dispersing pollutant emissions, as well as the calculation reliability of the average daily SPs concentration.

Table 1. Maximum permissible concentration (MPC) of the SPs for one-time (MPCot) and daily average (MPCda) measurements according to ГН 2.1.6.1338-03 (Russian Federation).

	TSP	**PM10**	**PM2.5**
MPCda, mg m^{-3}	0.15	0.06	0.035
MPCot, mg/m^{-3}	0.5	0,3	0.16

The gravimetric method is based on the mass concentration measurement of the SPs or their fractions by weighing. According to the measurement technique, the analyzed air is pumped through the filter that traps all SPs contained in the air. The precipitated SPs' mass is determined by the filter weight difference before and after sampling, and the concentration is calculated taking into account the volume of the pumped air during sampling. To measure the mass concentration of the SP fractions PM10 and PM2.5, additional devices are used that catch particles with size larger than the set size in the air flow (impactors), which are installed in the air intake tract in front of the filter. The advantage of the method is that it is a direct reference method for determining the SPs' mass concentration. The disadvantage of the gravimetric method is that the measurements have to be performed manually, and with the current state of the art, it is impossible to automate it for continuous measurements. The radiation method is based on the absorption of beta radiation by the SPs. According to the measurement technique:

- the analyzed air is pumped through the filter that captures all the SPs containing in the air,
- the filter is placed between the source and the beta radiation detector,
- the value of betta radiation absorbed by the filter-caught SPs is measured,
- SPs' mass is calculated,
- SPs' mass concentration is determined taking the sample pumped volume into account.

To determine the mass concentration of the SPs' fractions PM10 and PM2.5, impactors are used similarly to the gravimetric method.

The disadvantages of this method are:

- low sensitivity and, as a result, the need to carry out sampling for a long time (about 1 day), which does not allow for one-time measurements;
- high cost of the equipment and consumables.

The ultrasonic method is based on the change in the resonant frequency of the solid-state resonator when SPs deposit on its surface. In accordance with the measurement technique, the analyzed air is pumped in the way that SPs deposit on the surface of the resonator. SPs' mass is determined by change its resonant frequency in the ultrasonic range, and the mass concentration is calculated as the ratio of SPs' mass to the volume of the pumped analyzed air. The disadvantage of this method is the need to manually clean the resonator after each measurement, which does not allow the use of equipment for continuous measurements.

The optical method is based on measuring the particles size in the air stream by the reflection/scattering of laser radiation by their surface. The measurement method consists in pumping the analyzed air through the special optical system, where the laser beam irradiates the passing particles. The scattered radiation is detected by the receiver, and the particle size is calculated from the intensity of the scattered radiation. Knowing the density of the SP substance, determined experimentally or by calculation, the mass concentration of the SPs or their PM10 and PM2.5 fractions is calculated. The advantage of the method is the ability to measure SPs' and their fractions' concentration in a continuous mode at the maximum permissible concentration level, but the method is indirect, and for reliable determination of SPs' mass concentration, it is necessary to have data on SPs' density. This disadvantage is essential, since the types of SPs and, accordingly, their density in the controlled area can vary significantly depending on the time of year.

Thus, none of the existing methods provides the possibility of metrologically reliable determining of SPs and their PM10 and PM2.5 fractions in a continuous mode. The development of an installation for monitoring the concentration of suspended particles (dust) in the air atmosphere in a continuous mode is an urgent scientific, technical and practical task.
The practical relevance of the development is related by the need of transferring the State monitoring network of the Federal Service for Hydrometeorology and Environmental Monitoring from the mode of one-time to continuous measurements of pollutants in the atmospheric air up to year 2030.
Within the framework of national “Ecology” project the monitoring network is already being modernized including its technical means for continuous SPs measurement. Other possible consumers of such facility are:

- subordinate organizations of the regional ministries of ecology that monitor the state of the environment in the region,
- environmental services of large industrial enterprises (metallurgical plants, coal mining enterprises, etc.),
- small and medium-sized enterprises (thermal power plants, river and sea ports, etc.) and others.

MATERIALS AND METHODS

The optical principle of SPs size determining in continuous mode is used in the device being developed. SPs mass separation device (impactor) is applied to determine the SPs’ density. The measurement of the SPs concentration in the atmospheric air is regulated by the following standards and instructions:

- State Standard 17.2.3.01-86. Nature protection. Atmosphere. Rules for air quality control of settlements,
- RD 52.04.186-89, RD 52.04.186-89 Guidelines for air pollution control,
- RD 52.04.830-2015 Mass concentration of PM10 and PM2.5 suspended particles in atmospheric air. The method of measurement by the gravimetric method, etc.

According to these documents, the device must provide:

- discrete measurements of the RF content by gravimetric method
- continuous SPs concentration measurements with a frequency of at least 1 time in 20 minutes.
- SPs concentration measurements with a relative error not greater than 25% in the range from not more than MPCda to not less than 10 MPCot.

Discrete measurements are carried out with a frequency of 1 to 4 times a day to determine single values and during the day to determine the average daily values of the SPs concentration.
Taking into account the fact that the lowest MPCad is set for the PM 2.5 fraction and is 0.035 mg/m^3, and the total relative measurement error should not exceed 25%, air flow stabilization at a given level is provided by modern devices at a given level with a relative error of 5%, high-precision scales provide mass measurement with an error of 25% in the range from 0.01 mg, the mass of SPs at their content in the analyzed air at 0.035 mg/m^3, SPs amount deposited on the filter during sampling should be at least 0.050 mg. Since 0.050 mg of SPs is contained in 1.43 m^3 of air sampled with a concentration of 0.035 mg/m^3, the sampling rate should be at least 1 l/min.
In accordance with the requirements of regulatory documents, continuous measurements of the RF content in the air must meet the following conditions: the sensitivity of the method must not exceed 0.1 MPCda PM2.5 or 0.0035 mg; the device must provide continuous measurement of the SPs mass concentration in the atmospheric air by one of the reference methods (gravimetric, radiation or optical).
The device under development uses the method of filtering suspended particles in the air stream by their mass and size characteristics (linear size and density) using impactors and, at the same time, determining the granulometric composition of the initial and filtered flow by the optical method.

RESULTS AND DISCUSSION

The system consists of two systems connected by a common sampling path and a control unit. Operational principle of the system for measuring the PSs mass concentration of by gravimetric method in discrete mode is the following. The sample air, at the account of pump-created vacuum, is fed through the inlet pipe-sampling tract, then passes the impactor, the filtration unit, the gas consumption regulator (GCR) and is ejected by the pump into the atmosphere. SPs larger than 10 µm, in the range from 5 µm to 10 µm, in the range from 2.5 to 5 µm are deposited on the filters that are installed in the impactor’s respective stages, other SPs are trapped by the HEPA filter. The control unit provides the pump and the GCR control.

Filters installed in the impactor's cascades and in the filter blocks are weighed before and after sampling, the difference of the filters weights determines the SPs mass that is larger than 10 µm (stage 1, M10), larger than 5 µm (cascade 2, M5), larger than 2.5 µm (cascade 3, M2.5) and less than 2.5 µm (HEPA filter, M0).

SPs and their fractions mass concentration is calculated as follows:

$TSP = (M10+M5+M2.5+M0) / V_p$,

$PM10 = (M5+M2.5+M0)/V_p$,

$PM2.5 = (M2.5+M0)/V_p$,

where M is the SPs mass on the corresponding filter, V_p is the volume of the air passing through the cell of the analyzer during the sampling time.

System for the SPs mass concentration measuring in continuous mode is the following. The sample air, at the account of pump-created vacuum, is fed through the inlet pipe-sampling tract, then passes the impactor (without filters installed in the cascades), filter unit (without filter), the final cleaning filter, GCR and is ejected by the pump into the atmosphere. At the same time the analyzer 1, due to the vacuum created by its own pump, selects a sample through the outlet nozzle from the pipe point before entering the impactor, into its measuring cell, and determines the particles range by their sizes. The analyzer 2, due to the vacuum created by its own pump, selects a sample through the outlet nozzle from the pipe point after leaving the impactor, into its measuring cell, and also determines the particles range by their sizes. The control unit provides of the pump and the GCR control, and also receives data on the SPs size distribution from the analyzers and calculates the content of SPs and their fractions. SPs and their fractions mass concentration is calculated as follows: the maximum particle size at the output of the impactor is determined using the spectrum measured by the analyzer 2, the particle density is calculated using the following formula:

$\rho = (D_{max}/2.5)^2$ [g/cm^3],

where ρ is the particle density, D_{max} is the measured diameter of the maximum size particles in microns.

The SPs mass is determined from the SPs size spectrum measured by analyzer 1, in the size range from 0.2 microns to 2.5 microns, from 0.2 microns to 10 microns, and from 0.2 microns to 40 microns for PM2.5, PM10, and TSP, respectively, as follows. The number of particles in each band is multiplied by the mass of a single particle, which is defined by the average particle diameter (average between the maximum and minimum diameter in the range) and its density is determined by the analyzer's 2 spectrum. The particles mass in each range is summarized, and then the mass fractions of the SPs and the total mass of particles, TSP, and their mass concentration is calculated dividing by the volume of air passed through Analyzer 1 measuring cell.

The dust meter has been designed as a system of blocks connected aerodynamically and electrically (Fig. 1). These blocks are located inside of the protective housing.

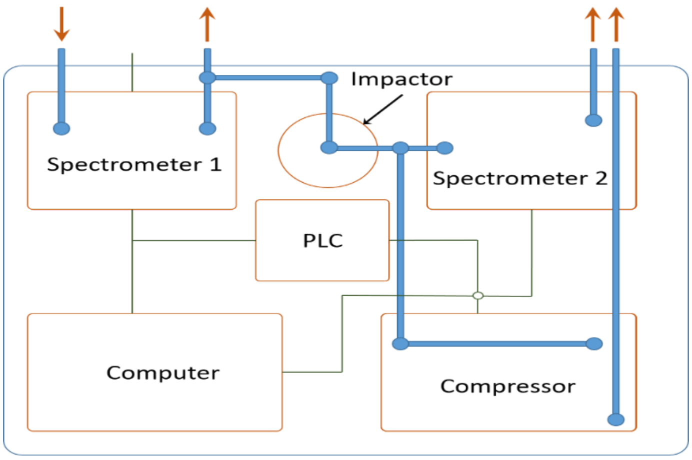

Fig. 1. Design of the dust metering system. Blue (bold) lines are aerodynamic connectors, green (thin) lines are electrical connectors.

The calculation of the suspended particles quantitative concentration by the optical method is reduced to the classical electrodynamics problem, solved by Gustav Mie in 1908, which is well suitable for particles with characteristic size less than 10 microns. Difficulties appear for particles with sizes larger than 10 microns. To avoid these problems, it was decided to use a certain approximation line that divided the particle sizes into two ranges. For larger particles the quantitative concentration was calculated by a special case of the Mie Scattering, namely Fraunhofer approximation.

The operation principle of the optical method for measuring the number and size of particles, as well as the optical system itself, which allows obtaining the necessary data, is shown in Fig. 2.

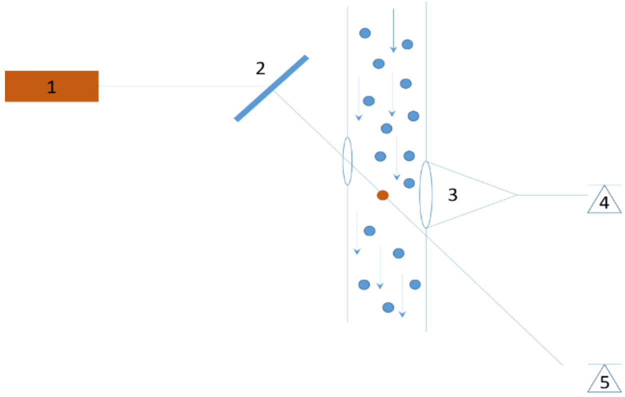

Fig. 2. Schematic diagram of the optical measuring part of the dust meter system.

Fig. 2 shows how the directed light stream from the LED radiation source (1) hits the mirror (2), which reflects the beam in the direction of the reference photodetector (5), passes through the lens that focuses the beam at the point (highlighted in color). At this point, the suspended particles are registered. Perpendicular to the flow, at an angle of 45 degrees to the specified beam, is the optical axis of the lens (3), which focuses the scattered color on the photodetector (4), which registers the suspended particles. The reference photodiode (5) stands in the direct beam area.Physical modeling of flow propagation along the described air routes was made in FlowVision software complex to optimize all route parameters. For this purpose, FlowVision numerically solved of the gas dynamics equations and the system of Navier-Stokes equations of a viscous compressible gas. Difference schemes with optimal splitting of operators in physical processes and spatial directions were used. 3D models of impactor and filters inner parts were created using SolidWorks software complex, and their. stl-copies were loaded into FlowVision projects for further numeric experiments. Adaptive coordinate grids were implemented with thickening in the places of bends, constrictions and obstacles in the airflow path. The problems of minimizing pulsations and the occurrence of vortices in the locations of the analyzers were solved. Also taking airflow simulation results into consideration, Mie scattering was modelled in the optical scheme using Mathcad before dust meter prototype creation. Both simulations were performed separately. We plan to unite them in our future work using Comsol and to compare modeling results with the prototype operation.

CONCLUSION

According to the results of the survey, the necessity of creating the system for monitoring the concentration of suspended particles in the atmosphere, ensuring industrial safety at enterprises, facilities and in rooms with high dust content was proved. Among the existing methods of measuring the dust concentration, the most suitable ones for the reference conditions were selected. The system, that combines optical and gravimetric methods for single and daily average measurements was proposed. Its design was developed. Mathematic modelling of flow propagation along the specified air routes was performed. The work of optical part was also imitated. These results will be used for the dust metering system prototype creation.

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Bibliographic information of this paper for citing:

Velichko, MA, Chernyavskikh, SD, Vitokhina, NN, Bugaevskaya, AN, Ostapenko, SI, Motkina, NN, Tsetsorina, TA, Mandrika, GV 2022, Physical modeling of various processes in development of the system for monitoring the concentration of suspended particles in the air. Caspian Journal of Environmental Sciences, 20: 165-170.