Monitoring pollution from ship power plants with laser technologies

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Abstract. When fuel burns in a ship engine, soot particles are formed that absorb flue gas toxic components. This absorption takes place on the surface of a particle. By solving an inverse problem involving light attenuation and diffraction on particles it is possible to obtain information on concentration and particle size distribution functions through space. An analysis has been complete on possibility of simultaneous assessment of concentration and particle size with a laser differential attenuation method. A four-wavelength laser system has been developed that allows measuring laser radiation attenuation signals using a differential extinction at three wavelengths and Mie scattering signal on aerosol particles at the fourth wavelength. From measured attenuated signals, an average volumetric-surface diameter of the aerosol particles was calculated. It has been shown that wavelengths of laser probing shall be selected depending on a soot particle size range. Application of the differential laser attenuation method to soot particles in ship power plant exhausts at several wavelengths allows simultaneously assess their concentration and size distribution. At that, laser wavelengths shall be selected depending on an expected range of variation of the Sauter mean diameter of the particles.

1. Introduction
In the context of increasing international commodity circulation, merchant shipping undergoes an intensive development; as a result, its environmental impact increases. At that, the highest concentration of vessels is found in harbor basins where their exhausts are dispersed, including through the boundary atmosphere layer over the harbor and adjoining residential and recreational zones. One of the most reliable, accurate and informative atmosphere research methods is optical sensing [1–3].

Exhausts of ship power plants consist of nitrogen oxides, carbon oxides (which are greenhouse gases), sulfur oxides, high-molecular weight aromatics and solid particles. The solid particles are soot that formed as a result of incomplete combustion of the heaviest fractions of fuel and engine oil, as well as metal oxides, sulfates and water. During their formation, these particles are saturated with a large number of hydrocarbon molecules, so when they get to pulmonary passages they are dangerous largely due to presence of polycyclic aromatic hydrocarbons (PAHs). Additional danger for respiratory organs stems from particles containing heavy metals and their compounds. At that, environmental regulations stipulate only total solid particles concentration.

Particle size largely determines behavior of the particle in the air and a degree of its implantation into human respiratory organs. So, large particles, larger than 10 μm usually accumulate in
pharyngonasal cavity and largely create only hygienic discomfort. Particle with the size less than 10 μm permeate tracheae and lung alveoles and thus are the most dangerous to human health. That is why in many countries, including Russia, there are differentiated hygienic standards for solid particle content in air. Besides, particle size significantly influences particle adsorption capability. When particle size decreases, its specific surface and thus adsorption capacity increases. In addition, soot particle size distribution may serve as an additional characteristic of heat exchange efficiency in the diesel engine combustion chamber. All this leads to a necessity to monitor not only concentration but particle distribution size as well.

2. Problem statement
There are several methods allowing for simultaneous measurements of concentration and particle size distribution. However, the desired methods shall allow for real-time measurements in order to timely identify and prevent reaching the admissible limit values.

In order to select optimal methods for soot concentration and particle size distribution monitoring it is necessary to analyze all the possible ranges of parameter variation.

Particle size in exhaust of ship power plants varies from 0.1 to 100 μm. The bulk of particles are in the range from 0.2 to 5.0 μm. At that, solid particle concentration in ship power plant exhaust reached 23 to 31 mg/m$^3$.

Papers [1, 4-6] consider laser-based measurement methods for concentration and particle size distribution functions as applied to particles formed by mechanical activation (fragmentation) of various materials, e.g., cement, lime, gypsum. The principle of measurement is derived from interaction of electromagnetic radiation with the particles, resulting in its attenuation and scattering. Characteristics of this attenuation and scattering of electromagnetic waves depend on physical, chemical and optical properties of the particles. In the context of possible soot particle size range, the most relevant parts of the electromagnetic spectrum are visible and near-infrared. By solving an inverse problem involving light attenuation and diffraction on particles it is possible to obtain information on concentration and particle size distribution functions.

In the research results in [4], there is a description of studying concentration and distribution functions for cement particles in a flow. The range of particle sizes was from 0.1 to 100 μm and more. An average geometric parameter that characterizes specific surface of particles is average particles size $d_{32}$ also known as Sauter mean diameter (SMD). It is a diameter of uniform spherical particles with a total surface area equal to that of the total surface area of all the poly-disperse particles in the same volume. This parameter primarily characterizes particle size distribution. At that, in various process limits, the value of $d_{32}$ is primarily in a range from 0.3 to 4.5 μm. Concentration of such particles is several dozens of mg/m$^3$ in atmospheric emissions and up to several dozens of g/m$^3$ in flows between process stages.

From comparison of the above mentioned size and soot particle concentration in ship power plant exhaust and particles obtained by mechanical activation it is evident that the ranges overlap. Thus, it may be concluded that it is possible to measure soot concentration and particle size distribution in ship power plant exhausts with the laser methods. The methods are based on the Mie scattering theory [7]. At that, efficient and quite reliable in implementation is a modified spectral transparency method, otherwise known as differential attenuation method.

The method consists in simultaneous probing of studied particles in an air flow with a laser radiation at several wavelengths. At that, wavelengths are selected in such a way that radiation attenuation on the particles is non-uniform and determined by a ratio between particle geometric sizes with considerations for their refraction index and wavelength. Differential attenuation of laser radiation contains useful information.

The differential attenuation method is based on solving the inverse problem [5, 8, 9] that may be represented as a function (1):
where \( \tau_\lambda \) is the absorbance; \( C_n \) is a total particulate count; \( \lambda \) is a wavelength of the probing radiation; \( Q \) is an attenuation efficiency factor for individual particles; \( l \) is an optical length of probing; \( x \) is a particle diameter; \( m \) is a complex refraction index of the particle material.

The average attenuation efficiency factor is calculated with the formula (2):

\[
\bar{Q}(x, \lambda, m) = \frac{\int_0^\infty x^2 \cdot Q(x, \lambda, m) \cdot f(x)dx}{\int_0^\infty x^2 \cdot f(x)dx}.
\]

Mass concentration of particles from the total particulate count is found with the formula (3):

\[
C_m = C_n \frac{\pi \cdot \rho_p}{6} \cdot \frac{\int_0^\infty x^3 \cdot f(x)dx}{\int_0^\infty x^2 \cdot f(x)dx}.
\]

Substituting in (1) the total particle count with a mass concentration we get the expression (4):

\[
\tau_\lambda = \frac{1.5 \cdot C_m \cdot l \cdot \bar{Q}(x, \lambda, m)}{\rho_p \cdot d_{22}},
\]

where \( \rho_p \) is the density of particle material.

Experimental measurement of absorbance and calculated Sauter mean diameter of particles allow for calculating the mass concentration of suspended solids with a formula (5):

\[
\tau_\lambda = \frac{1.5 \cdot C_m \cdot l \cdot \bar{Q}(x, \lambda, m)}{\rho_p \cdot d_{22}},
\]

The physical model of the method is based upon interaction between monochromatic radiation and polydisperse medium according to the Mie scattering theory [7] and preservation of invariance of the average effective attenuation factor with respect of the type of particle size distribution function [6].

The Sauter mean diameter of aerosol flows is determined from measurement of absorbance of the studied aerosol across several wavelengths and calculation of averaged effective attenuation factors for these wavelengths. The ratio between the measured absorbance values for two wavelengths is equal to a ratio of calculated average effective attenuation factors and express the function of the average particle size according to the formula (6) [6]:

\[
\frac{\tau_{\lambda_i}}{\tau_{\lambda_j}} = \frac{\bar{Q}(x, \lambda_i, m)}{\bar{Q}(x, \lambda_j, m)} = F_{ij}(d_{22}).
\]

The measurement range of average particle size is determined by the wavelengths of the probing radiation.

3. Laser installation and research methods

An optical train of the laser system is shown in Figure 1. The laser installation has the following principle of operation. Laser radiation sources 1 modulate the radiation at three wavelengths: 405, 1064, 650 nm. Along the laser ray paths there are wavelength filters 2, beam splitters 4, mirror 3, a plate with an opening 10, mirror system 9.
Figure 1. Optical train of the laser system: 1 – lasers operating at wavelengths of 650, 1064, 405 nm; 2 – wavelength filters; 3 – mirror; 4 – beam splitters; 5 – baseline optosensor; 6 – laser beam; 7 – aerosol flow; 8 – MSP optosensor; 9 – mirror system; 10 – a plate with an opening; 11 – ADC; 12 – telescope; 13 – light guide fiber; 14 – spectrometer; 15 – PC; 16 – laser operating at a wavelength of 532 nm; 17 – signal conditioning, recording and processing unit.

On the side opposite from the radiation sources there is an attenuated radiation optosensor 8. Radiation that did not pass through the measurement volume of the aerosol flow 7 by means of beam splitters 4 and mirror 3 reaches the baseline optosensor 5. In addition, the installation includes a signal conditioning, recording and processing unit consisting of measurement and baseline synchronous detectors, power amplifier and pulse generator [4]. Synchronous detection of measurement signals is intended to increase sensitivity of the optosensor device. Laser 16 generates radiation at a wavelength of 532 nm that falls onto the measurement volume of the aerosol flow 7 under a small angle $\theta \approx 0^\circ$ to the axis of a telescope 12, located to the same side of the aerosol flow as the laser 16. The focus of the telescope 12 is at the butt of the LED 13. This LED 13 is intended to introduce radiation to a spectrometer 14, which is serially connected to a PC 15.

A block diagram of the signal conditioning, recording and processing unit is shown in Figure 2. The laser system operates in the following way: lasers 1 generate radiation at three wavelengths (405 nm, 532 nm, 1064 nm) with a frequency of $5 \cdot 10^3$ Hz. In order to select required wavelengths in the modulated radiation, there are wavelength filters 2 set in the way of the laser beams.

Generated radiation pulse sequences pass through beam splitters 4. A portion of radiation that passed through the beam splitters 4, having been reflected off the mirror 3, reaches the baseline optosensor, while another portion passes through the mirror system 9 and aerosol flow 7. In front of the mirror system 9 there is a diaphragm intended to cut off the rays arising from multiple reflections when the beam passes beam splitters 4 and is reflected off the mirror 3. The mirror system 9 consists of two parallel mirrors.

The mirrors in the laser system in question are installed at an angle that provides nine passes of the beam through the aerosol flow. The radiation passing through the aerosol flow is being attenuated and reaches the optosensor 8. After that, the radiation passes through a differential amplifier and a
synchronous detector and then is again amplified by a differential amplifier. Laser signals arrive in the signal processing unit, from which they are transmitted to a PC. Signal processing unit uses six channels of the ADC.

Figure 2. Block diagram of a signal conditioning, recording and processing unit: 1 – laser source; 2 – optosensor; 3, 5 – differential amplifier; 4 – synchronous detector; 6 – ADC; 7 – personal computer; 8 – pulse generator; 9 – modulator; 10 – power amplifier.

Laser 16 generates radiation at a wavelength of 532 nm. The radiation, having been scattered in the aerosol flow, reaches the telescope 12. The rays from the telescope focus reach the input of the light guide fiber and then are passed to the spectrometer 14, where they are transformed into a digital signal and through a separate channel, different from the attenuation signals reach the PC 15 for further processing.

4. Discussion
The developed four-wave laser system allows measuring laser radiation attenuation signals using a differential extinction at three wavelengths and Mie scattering signal on aerosol particles at the fourth wavelength.

The Sauter mean diameter of aerosol particles may be found from a dependence of the average efficient attenuation factor on the average volume/surface diameter of the particles [4]. Dependence of the average attenuation efficiency factor on the Sauter mean diameter for three wavelengths is shown in Figure 3.

Known dependences of the average attenuation efficiency factor on Sauter mean diameter for three wavelengths were used to plot the ratios shown in Figure 4 and demonstrating the relations between the average attenuation efficiency factor at two wavelengths and Sauter mean diameter.

From [4], the calculated dependences of the Sauter mean diameter on ratio of averaged efficiency factors at two wavelengths are applicable to ratio of absorbance at the two wavelengths.

Wavelengths for laser probing are selected on the basis of possible range of variation of soot particle size \(d_{32}\). Their range of variation shall overlap with the part where there is a monotonous increase in the ratio between averaged efficiency factors at two wavelengths with increasing \(d_{32}\).
As it is evident from Figure 4, use of laser radiation wavelength in a range between 405 and 1064 nm allows measuring $d_{32}$ values in a range from 0.2 to 1.2 μm.
The following ratios were found for calculated absorbance values:

\[
\frac{\tau_{\lambda_{650}}}{\tau_{\lambda_{405}}} \cdot \frac{\tau_{\lambda_{1064}}}{\tau_{\lambda_{405}}} \cdot \frac{\tau_{\lambda_{1064}}}{\tau_{\lambda_{650}}}.
\]

For each measurement series, an average value of the Sauter mean diameter was calculated for values obtained at three wavelengths. For the obtained average values of \(d_{32}\) from each series, an average value was calculated that amounted to \(d_{32} = 0.61\ \mu m\).

As a result, laser attenuation signals were measured at three wavelengths using a developed laser installation as a part of a test bench. Measured laser attenuation signals allow calculating the values of mass concentration and Sauter mean diameter of aerosol particles.

5. Conclusion

It has been established that the size of particles adsorbing toxic components of flue gas in ship power plant exhaust varies between 0.1 and 100 \(\mu m\). In the context of possible soot particle size range, the most relevant parts of the electromagnetic spectrum are visible and near-infrared. By solving an inverse problem involving light extinction and diffraction on particles it is possible to obtain information on concentration and particle size distribution functions.

Laser attenuation signals were measured at three wavelengths using a developed laser installation as a part of a test bench, which allowed calculating the values of mass concentration and Sauter mean diameter of aerosol particles.

Application of the differential laser attenuation method to soot particles in ship power plant exhausts at several wavelengths allows simultaneously assess their concentration and size distribution. At that, laser wavelengths shall be selected depending on an expected range of variation of the Sauter mean diameter of the particles.

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