INTERFEROMETRIC COUNTERS OF AEROSOL PARTICLES (CURRENT STATUS AND METHODS OF DEVELOPMENT)

Yu.E. Pol'skii and N.V. Filippova

A.N. Tupolev State Technical University, Kazan'
Received July 15, 1994

The paper presents a comparative analysis of the accuracy characteristics of different types of photoelectric counters (PEC's). Their basic applicability limits have been analyzed. In this case primary emphasis is placed on the elimination of errors caused by the physical nature of particles. It is shown that this factor can be eliminated using interferometric counters of aerosol particles, in particular, those using radiation at different wavelengths. The paper describes the basic relations determining the metrological characteristics of such counters.

The enlargement of the field of application of photoelectric devices designed to measure the characteristics of aerosol media as well as the increase of the number of aerosol impurities and widening scope of their physical characteristics call for the development of more informative instruments with stringent requirements for the metrological characteristics. However, in the literature, especially in the Russian literature, there is scarcely any paper containing a generalized analysis of possibilities and limitations of the most promising photoelectric methods and their accuracy characteristics.

The basic parameters characterizing the photoelectric counters of any type are the following: the range of measurable particle size, their minimum measurable diameter and limiting measurable number density as well as the accuracy characteristics of measurement of these parameters. The paper presents an analysis of the existing methods of constructing the photoelectric counters taking into account the above parameters.

Spectrometers have the largest number of various modifications. The particle size is determined there by the pulse amplitude recorded at a photodetector output as the particle traverses the counting volume of the device. Because of the design simplicity such photoelectric counters have been adequately studied.[1–6] Principal disadvantages of such devices such, for example, as the dependence of the measurement results on the composition of particle material, ambiguity of the operating characteristics of devices, and stringent requirements for the amplitude characteristics of an electronic receiving$measuring channel, essentially limit the field of their application. The limiting characteristics of this method for constructing photoelectric counters and the average total error δ_Σ of particle size determination, caused by such factors as the finite size of input and output apertures, nonuniform illumination of the counting volume, and molecular scattering in the counting volume, are given in Table I.

At present the development of photoelectric counters is aimed at creating the devices that are not subject to the above$mentioned disadvantages. The two lines of development are evident, namely, the development of shadow and TV spectrometers (see, for example, Refs. 7$9, 10, and 11) and interferometric ones (see Refs. 12 and 13). The laser Doppler anemometers are most often used as the interferometric spectrometers.[14–17]

TABLE I. Limiting characteristics and the total error of different modifications of photoelectric counters.

Charac-teristics	Methods				
	Ampli-tude	Shadow	Interferometric		
			Doppler anemo-meters	Mono$ and polychromatic bands of different widths	Polychromatic equidistant interference bands
Particle size d, μm	0.3$60	5$300	0.3$L	5$120	0.3$0.7$L_{max}$
N_{max}	10^4	10^3	up to 10^6	10^5	$5\cdot10^5$
δ_Σ	> 0.5	> 0.5	$	$	< 0.2

So$called shadow spectrometers are classified among a large group of photoelectric counters. They comprise a device forming a collimated light beam, which is directed through the imaging optics to a photocell strip or a strip of light fibers 30$250 μm in diameter. When a particle traverses the collimated light beam, the particle shadow is formed casted on the photocell strip. A computer integrates signals from the photocells, selects them by amplitude, forms the criterion of particle size, and yields the information on the size of the particle that traversed the counting volume. The range of particle size measurable by these spectrometers is within 10 to 300 μm (for the device described in Ref. 9, $r_{min} \sim 5$ μm). A disadvantage of such devices is the large number of photocells (32 and more, for example, 256 in Ref. 9). In addition, the measurement error of minimum particle size exceeds 50 per cent.

In the TV spectrometers, the number of photocells is essentially decreased owing to the use of a TV tube. A light beam image and an image of particles traversing the light beam are formed on a sensitive element of the tube. Subsequent image scanning and analysis of recorded video signal are used to measure the particle size. However, the available TV spectrometers are very expensive, large, and massive and hence they cannot be used in field measurements.

The interferometric methods of determination of counting volume are used in the interferometric aerosol counters. A signal from the particle that traversed counting volume turns out to be modulated by amplitude (the function of size) and

0235-6880/95/04 337-03 $02.00

frequency (the particle velocity function). The degree of modulation of photocurrent M depends on the particle size and as $M = (I_{max} - I_{min})/(I_{max} + I_{min}) = 2J_1(\rho)/\rho$, where $J_1(\rho)$ is the first order Bessel function of the first kind, $\rho = 2\pi r/L$, r is the particle radius, and L is the period of interference pattern.[1]

Since the width of the interference band does not exceed $\lambda/2$, the minimum measurable size is considered to be $r = \lambda/4$. On the other hand, the sensitivity of standard photodetectors with allowance for the light scattering efficiency limits the minimum measurable particle diameter d_{min} by the value of the order of 0.3 μm (see Refs. 5, 6, 18, and 19). In accordance with the theory developed in Ref. 20, to minimize the errors due to the amplitude characteristics of electronic receiving channel, M_{max} may not exceed 0.9 and hence $r_{min} \geq 0.1L$. Since the degree of modulation M is ambiguous for the particles with $r > 0.55L$, the maximum size r measured by the interferometric methods is of the order of $L/2$.

Another limitation of the interferometric method is a comparatively narrow range of measurable particle size. However, it should be noted that the method enables one to measure the particle number densities (for minimum period $L = 1.5$ μm) up to 10^6 cm^{-3}.

To extent the capabilities of the interferometric methods it was suggested to form the polychromatic bands of light-shadow[21] or colored bands[22] of different widths in the counting volume. An essential advantage of these methods is counting of scattered signals what makes it possible to process the electric signals varying in a wide dynamic range of size. However, these methods are characterized by complexity of formation of the counting volume, small number of measurement subranges, and large size of measurable particles (larger than 5 μm) what enables one the use of the methods of mono- and polychromatic interference bands of different widths only for a limited class of problems under study.

To reduce the effect of ambiguity in determining the particle size, to increase the accuracy, and to extend the size range, as well as to increase the maximum measurable number densities, we proposed a new method of forming the band structure of the counting volume.[5,23] The essence of the proposed method is as follows. The equidistant interference bands with different periods L_i for different wavelengths λ_i are formed in the counting volume by means of the color-separating and converging optical systems. The light scattered by each particle traversing such counting volume in the direction perpendicular to the system of bands, is directed toward photodetectors. Each photodetector receives the radiation at one wavelength. The degree of modulation $(\Delta U/U_{max})_i = (U_{max} - U_{min})/U_{max}$ of signal at the output from each photodetector depends on the relationship between the particle diameter d and the step of the interference pattern L_i of each color.

The main advantage of the method is the ease of formation of equidistant bands with a required period using any standard method.

The minimum particle diameter $(d_{min})_{min}$ that can be recorded using this method is determined by the threshold sensitivity of receivers of scattered radiation and by the minimum formed period. The dependence of the value $(\Delta U/U_{max})$ on the particle diameter d is shown in Fig. 1. For all particles with the diameter d larger than $0.7L_i$ the function $(\Delta U/U_{max})$ is ambiguous. As a result, the range of measurable particle size for the periodic structure of one color is $[(d_{min})_i\,;\ 0.7L_i]$. Using the polychromatic interference patterns with different periods (for example, L_2 and L_3) we obtain for the particle with the diameter $d^* > 0.7L_i$ the different values of $(\Delta U/U_{max})_i$ at each wavelength. This enables us to eliminate the ambiguity of counts and simultaneously to increase the measurement accuracy due to less stringent requirements for electronic channel.

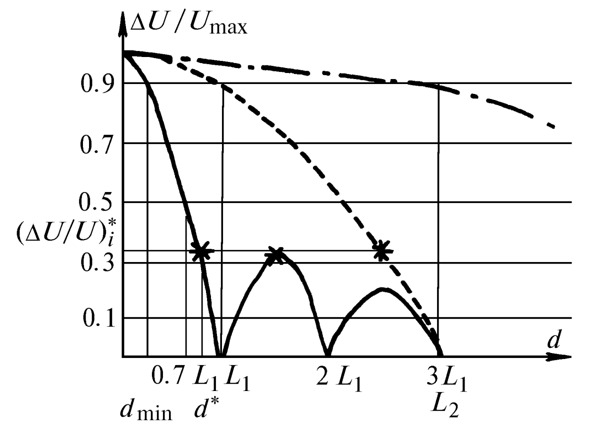

FIG. 1. Dependence of the function $(\Delta U/U_{max})$ on the particle diameter for different periods of the interference pattern (the method of polychromatic equidistant bands).

In accordance with the theory developed in Ref. 20, we may completely eliminate the ambiguity and keep the accuracy, the number of gradations, and measurement ranges constant with the minimum number of light sources if the counting volume is constructed based on the principle illustrated by Fig. 1. The value of L_{min} is chosen to be approximately equal to 3 d_{min} for the ratio $(\Delta U/U_{max})$ at the point d_{min} to be equal to 0.9. The value of d_{min} may correspond to the minimum diameter of particles to be recorded. Then each subsequent period must be about three times longer than the preceding one. The maximum size of a particle that can be recorded without significant errors d_{max} is equal to 0.7 L_{max}. Determination of the particle size based on the measured ensemble of the degree of modulation over the whole range of measurements enables us to impose much less stringent requirements for the linearity of the amplitude characteristics and the accuracy of threshold characteristics of comparators of electronic part of measuring channel.

Hence, it is expedient to improve further the equipment for investigating the disperse composition of aerosols by means of improvement of the interferometric methods owing to the independence of their results of the particle nature. A new method of polychromatic equidistant interference bands is free from main disadvantages of the interferometric methods, such as narrow interval of measurable size, ambiguity of operating characteristics, and stringent requirements for electronic-measuring channel. The technical state of the art allows recording, using the above-described method, such minimum particle size as by other photoelectric counters. The principle of constructing the counting volume enables one to decrease its dimensions down to 5 d_{max} along each axis and to measure the particle number density up to $5 \cdot 10^5$ cm^{-3}.

The performed analysis of error sources existing in this type of particle counters has shown that the requirements for the characteristics of the device to minimize the errors down to the values less than 10 per cent are technically feasible.

REFERENCES

1. S.P. Belyaev, N.K. Nikiforova, V.V. Smirnov, and G.I. Shchelchkov, *Opto–Electronic Methods of Aerosol Study* (Energoizdat, Moscow, 1981), 232 pp.
2. Y. Pui David and Y.H. Liu Benjamin, Phys. Scr. **37**, No. 2, 252$269 (1988).
3. H. G. Barth, Shao$Tang Sun, and R. M. Nickol, Anal. Chem. **59**, 142R$162R (1987).
4. E.A. Efremov, B.P. Kulakov, L.A. Ogarev, et al., "*Photoelectric counters of particles in liquid and gaseous technological media,*" Inform. Review No. 3770, Moscow (1985), 76 pp.
5. Yu.E. Pol'skii and N.V. Filippova, in: *Abstracts of Reports at the XIIth Interrepublican Symposium on Laser Radiation Propagation*, Tomsk (1993), p. 206.
6. Yu.E. Pol'skii and N.V. Filippova, in: *Abstracts of Reports at the IInd All–Union Conference on Optical Methods of Flux Investigation*, Novosibirsk, (1993), p. 31.
7. R.G. Knollenberg, in: *Proceedings of the Conference on Cloud Physics*, Boulder, USA (1976), pp. 554$561.
8. I.O.F. Wang and D.A. Fichenor, Appl. Opt. **20**, No. 8, 1367$1373 (1981).
9. F. Francini and G. Longobardi, Opt. Commun. **33**, No. 1, 1$3.
10. V.N. Panov and G.F. Yaskevich, Tr. Inst. Eksp. Meteorol., No. 7 (112), 36$48 (1984).
11. V.A. Malakhov and V.V. Smirnov, Tr. Inst. Eksp. Meteorol., No. 4 (38), 70$93 (1973).
12. E.K. Chekhovich and I.M. Lakoza, "*The device for determining particle size in flowing media,*" Inventor's Certificate No. 1679284 (USSR), Priority of September 29, 1988.
13. N.V. Goncharov, "*The device for determining the aerosol particle size in a flow,*" Inventor's Certificate No. 554466 (USSR), Bull. No. 14, 1977.
14. "*Method and device for measuring velocities and/or size of dispersion particles,*" Patent No. 2642839 (FR), Priority of February 9, 1989.
15. B.S. Rinkevichus, *Laser Diagnostics of Flows* (Power Institute Publishing House, Moscow, 1990), 288 pp.
16. S.D. Pinchuk, A.M. Skripkin, and A.A. Suplakov, Tr. Inst. Eksp. Meteorol., No. 13 (58), 162$170 (1976).
17. W.M. Farmer, Appl. Opt. **11**, No. 11, 2603$2612 (1972).
18. V.V. Sheiko, V.Yu. Aleksandrov, and A.A. Aksenov, Probl. Kontr. Zashch. Atmosf. Zagryazn., No. 13, 60$66 (1987).
19. Ya. Morita and M. Takagi, Utyu Kagaku kankyuse khokoku (JP), No. 8, 87$99 (1983).
20. G.I. Il'in and Yu.E. Pol'skii, Itogi Nauki Tekhn., (Radiotekh.) **39**, 67 (1989).
21. I.I. Vasil'ev, G.I. Il'in, and Yu.E. Pol'skii, "*Method for measuring microparticle size,*" Inventor's Certificate No. 1032370 (USSR), Bull. No. 28, 1983.
22. I.I. Vasil'ev, D.B. Gorbachev, G.I. Il'in, and Yu.E. Pol'skii, "*Method for measuring microparticle size,*" Inventor's Certificate No. 1434333 (USSR), Bull. No. 40, 1988.
23. Yu.E. Pol'skii and N.V. Filippova, "*Method for measuring microparticle sizes,*" Inventor's Application No. 93028121/02, Priory of June 4, 1993.