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MEASUREMENT OF WAVELENGTH-DEPENDENT EXTINCTION TO DISTINGUISH BETWEEN ABSORBING AND NONABSORBING AEROSOL PARTICULATES

Rainer Portscht

Translation of "Wellenlängenabhängige Extinktionsmessung zur Unterscheidung absorbierender und nicht-absorbierender Aerosolpartikelen," Staub-Reinhaltung der Luft, Vol. 37, Feb. 1977, pp. 70-76.

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16. Abstract

It has been found during measurements of spectral transmission factors in smoky optical transmission paths that there is a difference between wavelength exponents of the extinction cross section of high absorption capacity and those of low absorption capacity. The paper gives a theoretical explanation of this behavior and it is shown that, in certain cases, it is possible to obtain data on the absorption index of aerosol particles in the optical path by measuring the spectral decadic extinction coefficient at, at least, two wavelengths. In this manner it is possible, for instance, to distinguish smoke containing soot from water vapor.

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MEASUREMENT OF WAVELENGTH-DEPENDENT EXTINCTION TO DISTINGUISH BETWEEN ABSORBING AND NONABSORBING AEROSOL PARTICULATES[1]

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Ulm

1. Introduction /71

For continuous monitoring of smoke and dust content of the air extinction measuring instruments based on the double beam compensation method have proved themselves many times over in practice.

If a monochromatic measuring setup is selected, extinction measuring instruments determine the spectral decadic extinction coefficient $m(\lambda_Q)$ for the wavelength of the test light λ_Q(DIN 1349).

$$m(\lambda_Q) = \frac{1}{L} \log\left[\frac{1}{\tau_i(\lambda_Q)}\right] \quad (1)$$

with

$$\tau_i(\lambda_Q) = \frac{\Phi_{\lambda 1}(\lambda_Q)}{\Phi_{\lambda 0}(\lambda_Q)} = e^{-C_{Ext}(\lambda_Q, d, M_1, M_2)\, z\, L} \quad (2)$$

In these equations L is the length of the measurement path, $\tau_1(\lambda_Q)$ is the degree of spectral (pure) transmission at the test wavelength λ_Q, z is the particle concentration and C_{Ext} is the extinction cross-section of the aerosol particles in the light path. $\Phi_{\lambda 0}(\lambda_Q)$ is the spectral radiant flux emitted by the source of radiation and $\Phi_{\lambda I}(\lambda_Q)$ is the spectral radiant flux diminished by the extinguished portion at the point of the radiation receptor for the test wavelength λ_Q. If Eq. (2) is substituted in Eq. (1),

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1. The fundamental studies and measurements for this article were carried out during the author's work with the "Automatic Fire Detection" group at the Institute for Electronic Communication Engineering of Aachen Technische Hochschule.

* Numbers in the margin indicate pagination in the foreign text.

this gives the following equation taking into consideration the relationship $\log x = \log c \cdot \ln x = 0.443 \cdot \ln x$:

$$m(\lambda_Q) = 0{,}433 \cdot C_{Ext}(\lambda_Q, d, M_1, M_2) \cdot z \tag{3}$$

From this it follows that the decimal spectral extinction coefficient $m(\lambda_Q)$ is proportional to the product of the extinction cross-section C_{Ext} times the particle concentration z. In an approximate way this equation is also valid for a non-monochromatic measuring setup [1] insofar as the wavelength interval $\lambda_1 \leq \lambda \leq \lambda_2$ is not selected too large.

The extinction cross-section characteristically depends on the wavelength of the test light, the size of the particles (diameter d or a suitable parameter of grain size distribution) and the optical constants (refraction index M_1 and absorption index M_2). If for a given particle diameter or a given grain size distribution for the particles one plots the extinction cross-section over the wavelength, then this curve is a function only of the optical constants M_1 and M_2.

In this paper it is shown that it is possible by measuring the wavelength-dependent decimal spectral extinction coefficient to obtain data on whether the aerosol particles in the light path are absorbent or transparent.

Starting with the results of few transmittance measurements in smoke-filled optical transmission paths a theoretical estimate of the behavior of absorbent and slightly or non-absorbent particles in the light path of extinction-measuring instruments is carried out. In the range of wavelengths studied the extinction cross-section and scattering cross-section can be calculated according to the Rayleigh approximation.

The difference in behavior of absorbent and non-absorbent particles in relation to light extinction as a function of wavelength forms the basis of a proposal to expand the use of current extinction-measuring instruments and determine the extinction coefficient for two appropriate wavelengths. In this way it is possible to eliminate the effect of the particle concentration and obtain more exact data on the optical properties of the aerosol particles, and in particular to distinguish between absorbent and slightly or non-absorbent particles. This has important practical implications, if, for example, it is desired to distinguish between smoke and dust or water vapor or if different types of smoke or dust are to be distintuished from one another.

2. Extinction Coefficient of Various Types of Smoke as a Function of Wavelength Determined from Transmittance Measurements

Within the context of a study entitled "The Calculation and Measurement of Extinction Properties of Smoke in the Optical Spectral Region" [2] transmittance measurements were carried out in smoke-filled optical transmission paths.

The measuring apparatus consisted of a source of radiation (chromium-nickel heating rods or a reflector incandescent lamp), a smoke channel and an infrared spectrophotometer. Different types of smoke were produced in a specified manner in the smoke channel. The density of the smoke in the channel was monitored with an additional extinction-measuring device. For each concentration of particles of a give type of smoke produced the transmittance $\tau_1(\lambda)$ was determined in the range of wavelenghts from $\lambda = 0.4\mu m$ to $\lambda = 10\mu m$. It was setup as the quotient formed by the spectral radiant flux $\Phi_{\lambda 1}(\lambda)$ over the spectral radiant flux $\Phi_{\lambda 0}(\lambda)$. The index 1 means that extinguishing aerosol particles were found in the light path, whereas the index 0 indicates that no extinguishing particles were present in the light path. After standardizing the measured transmittance curves as a function of wavelength on a reference concentration z_0 the product of the average extinction cross-section times /72 the reference particle concentration ($C_{Ext} \cdot z_0$) was determined and plotted in a double log scale over the wavelength. With the exception of a calibration factor, this quantity corresponds to the spectral decimal (or natural) extinction coefficient (cf. Eq. (1) and (2)). Fig. 1 shows a few typical results.

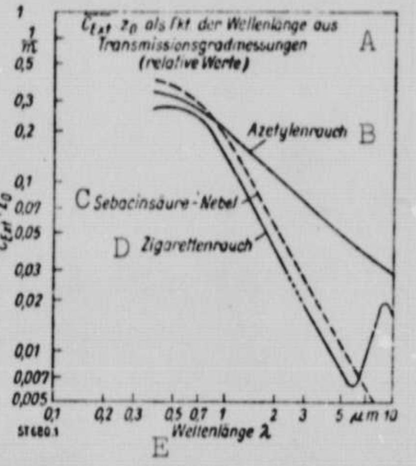

Fig. 1. $C_{Ext}(\lambda) \cdot z_0$ as a fun-function of wavelength taken from transmittance measurements (comparison of acetylene smoke, cigarette smoke and sebacic acid mist, relative values).

Key: A) $C_{Ext} \cdot z_0$ as a function of wavelength from transmittance measurements (relative values)
B) Acetylene smoke
C) Sebacic acid mist
D) Cigarette smoke
E) Wavelength

For sebacic acid mist, which was used to calibrate the measuring apparatus, and for acetylene smoke and cigarette smoke, the product $C_{Ext} \cdot z_0$ is plotted in Fig. 1 as a function of the wavelength. A striking feature is the difference in the wavelength exponent of the function $C_{Ext} \cdot z_0$ for acetylene smoke and cigarette smoke at wavelengths above 1μm.

This difference also appeared with other types of smoke. Thus it was found that with smoke, which resulted from the carbonization at low temperatures of cellulose-containing substances (such as posterboard, small wooden plates, tobacco or sack cloth), a smaller drop occurred in the graph of $C_{Ext} \cdot z_0$ over wavelength than with smoke which was produced by burning petroleum products (such as heating oil, acetylene, polyurethane and rubber tubing). These two types of smoke can clearly be distinguished from one another by their color just by irradiating them with natural light ("white" and "black" smoke). As an explanation for the difference in color and the difference in the graph of $C_{Ext} \cdot z_0$ over wavelength it has already been suggested in [2] that obviously the optical constants M_1 and M_2 for the particles in the light path are determining factors for the difference in behavior. For smoke from petroleum products basically consists of soot particles and smoke from cellulose-containing substances consists of condensation nuclei with a film of water or of tar droplets. From this it can be concluded that the wavelength exponent of the extinction cross-section is influenced by the optical constants M_1 and M_2.

In what follows a theoretical reason for this empirically determined behavior of aerosol particles will be deduced. In so doing, consideration is extended to non-absorbent particles (water droplets).

<u>3. Theoretical Estimation of the Wavelength Exponent of the Extinction Cross-Section of Absorbent and Non-Absorbent Aerosol Particles</u>

For homogeneous, isotropic, spherical particles with a diameter d and optical constants M_1 and M_2 (refraction index and absorbtion index) the extinction cross-section can be calculated as a function of the wavelengths λ according to the Mie theory [3-7]:

$$C_{Ext} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1)\, Re\{\underline{a}_n + \underline{b}_n\} \qquad (4)$$

The complex variables a_n and b_n are called Mie coefficients, which in turn via Riccati-Bessel and Hankel function are dependent on the complex refraction index M M_1 jM_2 and the magnitude $\alpha = \pi d/\lambda$. Besides the assumption that the particles are homogeneous, isotropic, spherical and monodisperse and that monochromatic primary radiation and single scattering exists, it is, to begin with, furthermore assumed that the complex refraction index $\underline{M}$ is not wavelength-dependent.

As follows from [2], all of the aerosols studied had grain size distribution with maximums less than 0.5μm. Thus for the magnitude $\alpha = \pi d/\lambda$ in the wavelength range now under consideration ($1\ \mu m \leq \lambda \leq 10\ \mu m$) it turns out that $\alpha < 1$ or even $\alpha \ll 1$..

For the condition $\alpha \ll 1$, which is met for small particle diameters and large wavelengths, the calculation of the extinction cross-section according to the Mie theory is simplified, so that the Rayleigh approximation can be used to describe the extinction of light by aerosol particles.

3.1 Rayleigh Approximation for Absorbent Particles

In the region of the Rayleigh approximation ($\alpha \ll 1$) the following equation follows for the first Mie coefficient [6]:

$$\underline{a_1} = j \cdot \alpha^3 \cdot \frac{2}{3} \cdot \frac{\underline{M}^2 - 1}{\underline{M}^2 + 2} \qquad (5)$$

The variables $\underline{a_2}$ and $\underline{b_1}$ are proportional to α^5. The variable $\underline{b_2}$ is proportional to α^7. Therefore, just like all higher Mie coefficients, these variables are ignored with respect to a_1. Thus, from Eq. (4) the following equation follows for the extinction cross-section:

$$C_{Ext} \approx \frac{\lambda^2}{2\pi} \cdot 3 \cdot Re\left\{ j\alpha^3 \cdot \frac{2}{3} \cdot \frac{(M_1 - jM_2)^2 - 1}{(M_1 - jM_2)^2 + 2} \right\} \qquad (6)$$

Whence after a brief calculation we obtain

$$C_{Ext} = 6 \frac{\pi^2 d^3}{\lambda} \cdot \frac{|M_1 M_2|}{(M_1^2 - M_2^2 + 2)^2 + (2M_1 M_2)^2} \qquad (7)$$

and

$$Q_{Ext} = \frac{C_{Ext}}{(\pi d^2/4)} = 24 \frac{\pi d}{\lambda} \cdot \frac{|M_1 M_2|}{(M_1^2 - M_2^2 + 2)^2 + (2M_1 M_2)^2} \qquad (8)$$

A check for the validity of Eq. (7) is obtained by comparing the values calculated exactly according to the Mie Theory with the help of computer programs with the values calculated according to Eq. (7). As an example, let the following values be substituted in Eq. (7): d = 0.2 µm, λ = 10 µm, M_1 = 1.96, M_2 = 0.66 (optical constants of soot). From Eq. (7) one obtains

$$C_{Ext} = 1.71 \cdot 10^{-3}\ \mu m^2 .$$

This value can also be read from Fig. 2.

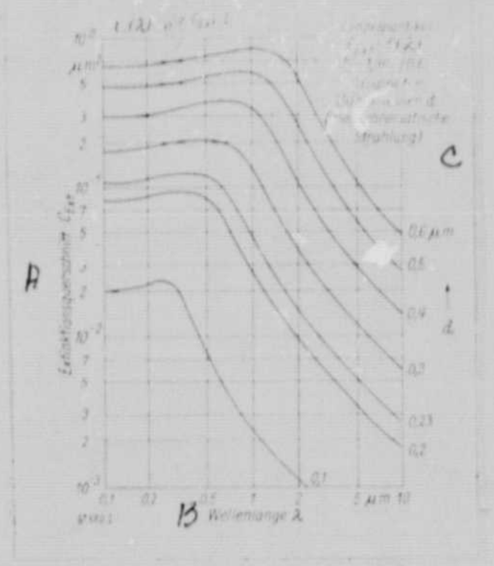

Fig. 2. Extinction cross-section as a function of wavelength for a monodispersion and complex refraction index of soot $\underline{M}$ = 1.96-j0.66.

Key: A) Extinction cross-section
B) Wavelength
C) Individual particle, $C_{Ext} \cdot f(\lambda)$, M = 1.96-j0.66, parameter: diameter d (monochromatic radiation)

Fig. 2 shows the extinction cross-section C_{Ext} as a function of the wavelengths in a double log scale. The calculation was carried out exactly for monochromatic radiation and individual particles according to the Mie theory with the help of computer programs. The parameter for the curves in Fig. 2 is the particle diameter d. The complex refraction index was assumed to be independent of wavelength. Mie coefficients with respect to a_1 were ignored. From Eq. (4) range of visible light [4] [sic].

For further consideration it is important with respect to Eq. (7) that the extinction cross-section $C_{Ext}(\lambda)$ of absorbent particles in the region of the Rayleigh approximation is inversely proportional to the wavelength (wavelength exponent η = -1).

A proof of the correctness of this estimate is again found in the graph of the extinction cross-section over wavelength in Fig. 2. For wavelengths greater than 5 μm the wavelength exponent can be read as the slope of the tangent to the plotted $\eta \approx -1$ curves.

A graph corresponding to Fig. 2 is obtianed if one forms the extinction effect factor $Q_{Ext} = C_{Ext}/(\pi d^2/4)$ and plots it over the wavelength.

It can also be seen in Fig. 3 that at wavelengths greater than 5 μm the wavelength exponent is $\eta \approx -1$, as is given by Eq. (8).

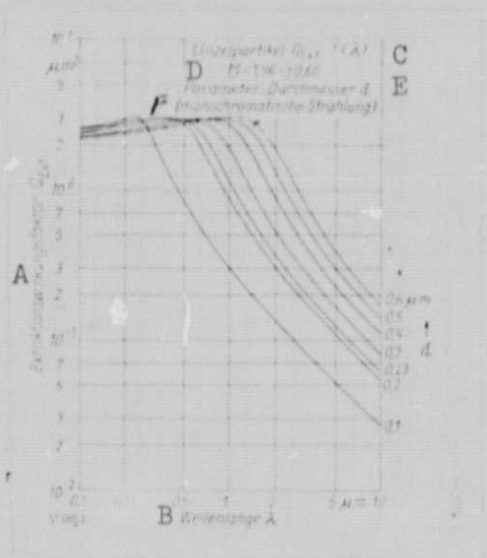

Fig. 3. Extinction effect factor as a function of wavelength for a monodispersion and complex refraction index of soot $\underline{M}$ = 1.96-j0.66.

Key: A) Extinction effect factor Q_{Ext}
B) Wavelength
C) Single particleQ$Q_{Ext}\cdot f(\lambda)$
D) M = 1.96-j0.66
E) Parameter: diameter d
F) Monochromatic radiation

The group of curves in Fig. 3 can be reduced to a single curve if the extinction effect factor Q_{Ext} is plotted over the standardizing magnitude $1/\alpha = \lambda/(\pi d)$ (upper curve in Fig. 4):

$$Q_{Ext}\left(\frac{\lambda}{\pi d}\right)_R = f\left(\frac{1}{\alpha}\right).$$

The index R indicates the optical constants for soot for which the graph drawn of the extinction effect factor was calculated. Standardization to $\lambda/(\pi d)$ produces a horizontal shift in the collection of curves shown in Fig. 3. In Fig. 4, for constant diameters d, a wavelength scale can be used at any time in place of the scale $1/\alpha = \lambda/(\pi d)$ along the abscissa,

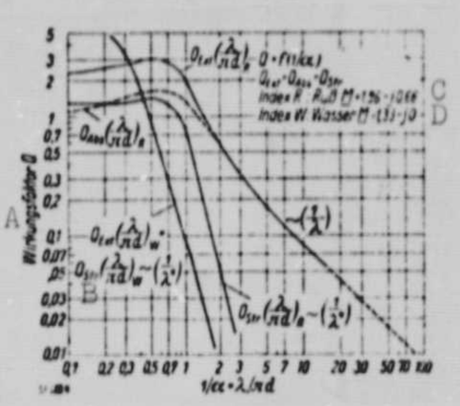

Fig. 4. Extinction effect factor, absorption factor, and scattering effect factor for soot ($\underline{M}$ = 1.96-j-0.66) and extinction effect factor for water ($\underline{M}$ = 1.33-j0) as a function of $1/\alpha = \lambda(\pi d)$ for monodispersion.

Key: A) Effect factor Q
B) Str = Scattering
C) Soot
D) Water

but this shifts horizontally as a function of d.

Also of interest is how the extinction effect factor Q_{Ext} is made up as a sum of the scattering effect factor Q_{Str} and the absorption effect factor Q_{Abs}. The absorption effect factor for soot was also calculated according to the Mie theory and is shown by the broken line in Fig. 4. As shown by the graph, for values of $1/\alpha = \lambda/(\pi d) > 2.5$ in the region of the Rayleigh approximation only the absorption of the particles in the light path is a determining factor for the graph of

$$Q_{Ext}\left(\frac{\lambda}{\pi d}\right)_R = f\left(\frac{1}{\lambda}\right)$$

Only for values of $1/\alpha < 2.5$ does the scattering of the soot particles produce a quantitatively significant contribution.

The approximation of the extinction cross-section and of the extinction effect factor given in Eq. (7) and Eq. (8) is no longer valid, however, if the absorption index M_2 of the particles goes to 0.

3.2 Rayleigh Approximation for Non-Absorbent Particles

If M_2 is set equal to 0 in Eq. (7) or Eq. (8), then C_{Ext} also equals 0. The reason for this can be seen in the derivation according to Eq. (5) and Eq. (6), because with a vanishing immaginary part of the complex refraction index ($M_2 \rightarrow 0$) the

Mie coefficient a_1 is always imaginary and, according to Eq. (4), the real part of an imaginary quantity is zero. Therefore, for the case of non-absorbent particles the approximation according to Eq. (5) is not permissible, but rather additional terms with higher powers of α must be considered.

Starting with the series expansion of the Bessel functions, one obtains the following equation for the first Mie coefficients:

$$\underline{a}_1 = \frac{\alpha^3}{3} \cdot \frac{1}{\frac{\alpha^3}{3} - j\frac{1 + \underline{M}^2/2 - 0.1(2\underline{M}^2\alpha^2 - 5\cdot\alpha^2 + \underline{M}^2(\underline{M}^2\alpha^2 + 5\alpha^2))}{1 - \underline{M}^2 - 0.1(2\underline{M}^2\alpha^2 + \alpha^2 + \underline{M}^2(\underline{M}^2\alpha^2 + 2\alpha^2))}} \tag{9}$$

and from this, ignoring the members of the second term of the denominator containing α^2, we obtain:

$$\underline{a}_1 \approx \frac{\alpha^3}{3} \cdot \frac{1}{\frac{\alpha^3}{3} - j\frac{1 + \underline{M}^2/2}{1 - \underline{M}^2}} = \frac{\alpha^3}{3} \cdot \frac{\frac{\alpha^3}{3} + j\frac{1 + \underline{M}^2/2}{1 - \underline{M}^2}}{\left(\frac{\alpha^3}{3}\right)^2 + \left(\frac{1 + \underline{M}^2/2}{1 - \underline{M}^2}\right)^2} \tag{10}$$

In the denominator of Eq. (10) one also ignores the expression $(\alpha^3/3)^2$ considering the second term, then we obtain the following for the real part of a_1: /74

$$Re\{\underline{a}_1\} \approx \frac{\alpha^6}{9} \cdot 4 \cdot Re\left\{\frac{(\underline{M}^2 - 1)^2}{(\underline{M}^2 + 2)^2}\right\} \tag{11}$$

Thus, according to Eq. (4) one obtains

$$C_{1a} = \frac{\lambda^2}{2\pi} \cdot 3 \cdot \frac{\alpha^6}{9} \cdot 4 \cdot Re\left\{\frac{(\underline{M}^2 - 1)^2}{(\underline{M}^2 + 2)^2}\right\} \tag{12}$$

or

$$C_{1a} = \frac{2}{3}\pi^5 \frac{d^6}{\lambda^4} \cdot Re\left\{\frac{(\underline{M}^2 - 1)^2}{(\underline{M}^2 + 2)^2}\right\} \tag{13}$$

For non-absorbent particles $\underline{M} = M_1 \cdot (M_2 = 0)$ and

$$C_{Ext} = \frac{2}{3}\pi^5 \frac{d^6}{\lambda^4} \cdot \frac{(M_1^2-1)^2}{(M_1^2+2)^2} \qquad (14)$$

This approximation is alos obtained if the scattering corss-section of non-absorbent particles is determined directly. The following equation applies [in (15)-(18), Str = scattering]:

$$C_{Str} = \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1)\{|\underline{a}_n|^2 + |\underline{b}_n|^2\} \qquad (15)$$

If one again uses the approximation according to Eq. (5) for the first Mie coefficient, then one obtains:

$$C_{Str} = \frac{\lambda^2}{2\pi} \cdot 3 \cdot \frac{4}{9} \cdot \alpha^6 \left|\frac{\underline{M}^2-1}{\underline{M}^2+2}\right|^2 \qquad (16)$$

$$C_{Str} = \frac{2}{3}\pi^5 \frac{d^6}{\lambda^4} \cdot \frac{(M_1^2-M_2^2-1)^2+(2M_1M_2)^2}{(M_1^2-M_2^2+2)^2+(2M_1M_2)^2} \qquad (17)$$

For non-absorbent particles ($M_2 = 0$) we obtain

$$C_{Str} = \frac{2}{3}\pi^5 \frac{d^6}{\lambda^4} \cdot \frac{(M_1^2-1)^2}{(M_1^2+2)^2} \qquad (18)$$

An important point with respect to Eq. (14) and Eq. (18) is that the scattering cross-section of non-absorbent particles, which with a lack of absorption equals the extinction cross-section of the particles, is inversely proportional to the fourth power of the wavelength (wavelength exponent $\eta = -4$).

In Fig. 4 is plotted the scattering cross-section of soot particles (R index) and the extinction cross-section of water droplets (W index) over $1/\alpha = \lambda/(\pi d)$ in a double log scale. The units along the abscissa and ordinate are chosen to be identical. It is obvious that the scattering cross-section of absorbent and non-absorbent particles in the range of the Rayleigh approximation follows the derived $1/\lambda^4$ law.

3.3 Implications for Extinction Measuring Techniques

Between the two limiting cases of strongly absorbent particles (e.g. soot) and non-absorbent particles (e.g. water droplets), the extinction cross-section of which follow a $1/\lambda$ and $1/\lambda^4$ law respectively, there is a sliding transition as will be explained by referring to Fig. 5.

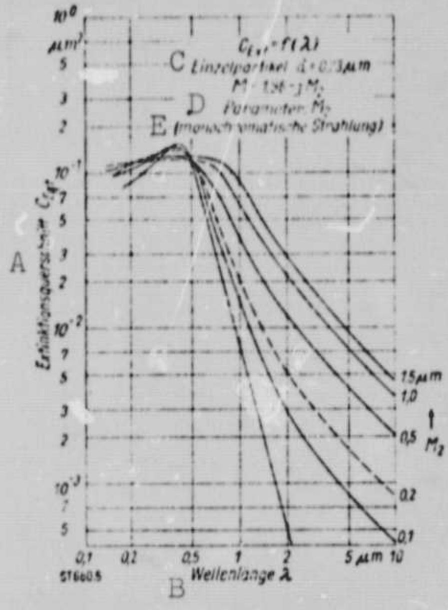

Fig. 5. Extinction cross-section as a function of wavelength for a mondispersion (d = 0.23 µm) and a refraction index of M_1 = 1.96. Parameter: absorption index M_2.

Key: A) Extinction cross-section
B) Wavelength
C) Single particle
D) Parameter
E) Monochromatic radiation

In Fig. 5 is plotted the extinction cross-section of particles with a different absorption index M_2 as a function of the wavelength in a double log scale. The calculation was carried out for spherical, homogeneous, isotropic particles with a diameter d (monodispersion, here d = 0.23 µm). The refraction index used was M_1 = 1.96 (soot), and the absorption index was varied between M_2 = 0 and M_2 = 1.5.

It is obvious from Fig. that the extinction cross-section is strongly dependent on the absorption index M_2 with the two limiting cases of wavelength exponents $\eta = -1$ for absorbent particles ($0.1 < M_2 < 1.5$) at wavelengths of $\lambda > 5$ µm and $\eta = -4$ for non-absorbent particles ($M_2 = 0$) at wavelengths of $\lambda > 0.5$ µm as well as the transition region between these two cases.

It can also be seen that the effect of the refraction index M_1 on the graph of C_{Ext} (λ) is much smaller than the effect of the absorption index M_2. From this it follows that by measuring the extinction coefficient as a function of wavelength or with 2 appropriate wavelengths absorbent particles can be distinguished from non-absorbent or slightly absorbent particles because the wavelength exponent of the extinction cross-section can be used as a measure for the absorption index of aerosol particles in the light path.

This regularity is also valid in the case which shows up in practice if the grain size distribution of the particles is described by a polydispersion, if the dependence on wavelength of the refraction and absorbtion index is taken into consideration and a non-monochromatic measuring setup is selected [1,8,9]. Calculations performed for standard logarithmic distributions [4,5,7] have shown that the equations derived above are also valid with still good approximation in this generalized case as long as the condition for the Rayleigh approximation is fulfilled:

$$\left(x = \frac{\pi d}{\lambda} \ll 1\right).$$

i.e., as long as the diameters of the particles are small with respect to the wavelength of the test light.

To this end let us consider Fig. 6 as an example.

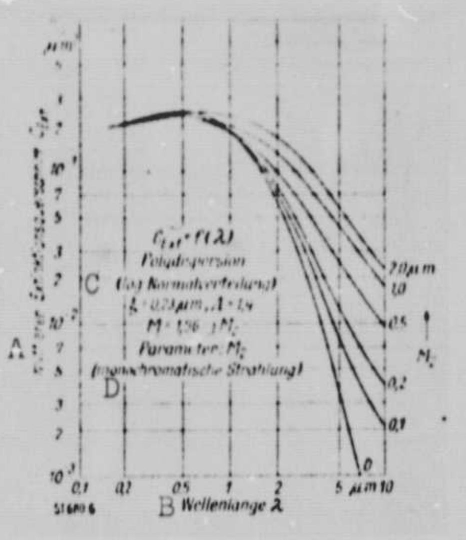

Fig. 6. Average extinction cross-section as a function of wavelength for polydispersion (log of standard distribution $\zeta = 0.23\ \mu m$, $\Lambda = 1.4$ and refraction index $M_1 = 1.96$. Parameter: absorption index M_2.

Key: A) Average extinction cross-section
B) Wavelength
C) Log standard distribution
D) Monochromatic radiation

In Fig. 6 is plotted the average extinction cross-section as a function of wavelength for a logarithmic standard distribution with a median value of $\zeta = 0.23\ \mu m$ and a spread of $\Lambda = 1.4$ and for a refraction index of $M_1 = 1.96$. The absorption index M_2 was varied. As in Fig. 5, the two /75
limiting cases for absorbent and non-absorbent particles can be recognized by the wavelength exponents $\eta \approx -1$ and $\eta = -4$ at wavelengths of $\lambda > 5\ \mu m$, and also transition between these two cases at wavelengths of $\lambda > 1\ \mu m$. Due to the fact that according to the logarithmic standard distribution not just one particle diameter but various particle diameters affect the average extinction cross-section in varying amounts, a certain integration effect takes place over the wavelength. The curves of the polydispersion are flatter and less curved than the monodispersion curves.

In addition, another special feature should be pointed out, namely that the absorbent particles may scatter more than the transparent particles. In this connection we will once again consider Eq. (17).

Let $R(M_1,M_2)$ stand for the factor given by the last fraction in Eq. (17) -- this factor specifies the dependence of the scattering cross-section on the optical constants:

$$R(M_1,M_2) = \frac{(M_1^2 - M_2^2 - 1)^2 + (2M_1M_2)^2}{(M_1^2 - M_2^2 + 2)^2 + (2M_1M_2)^2} \qquad (19)$$

and

$$C_{str} = \frac{2}{3}\pi^5 \frac{d^6}{\lambda^4} \cdot R(M_1,M_2) \qquad (20)$$

[str = scattering].

This factor will be discussed in more detail below. In Fig. 7 $R(M_1,M_2)$ is shown graphically as a function of the refraction index M_1 with the absorbtion index M_2 as the variable. The scale is linear.

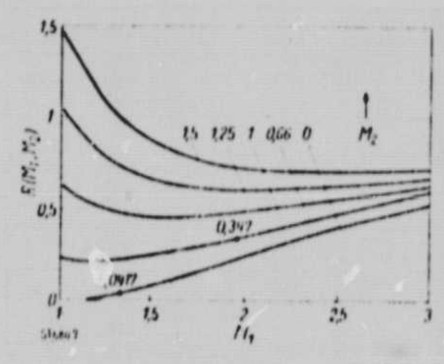

Fig. 7. $R(M_1,M_2)$ factor as a function of the refraction index M_1. Variable: absorption index M_2

A remarkable and unexpected fact here is the increase in the $R(M_1,M_2)$ factor and with it the increase in the scattering cross-section as a function of M_2 if the particles in the light bath are not transparent ($M_2 = 0$) but absorbent ($M_2 > 0$). As an explanation for why absorbent particles have a stronger scattering effect than transparent particles, it is suggested in [6] that according to Huyghens principle any inhomogeneity in the medium of propagation (i.e. within the particles) causes a disturbance of the primary light wave giving rise to a scattered wave. If the particles in the light wave possess an additional absorbtion component, then the scattered portion of the particles also increases accordingly, among other things also because for the small particles in the Rayleigh region the optical path distances within the particles is so small that the internal stray light portions cannot be significantly weakened by absorbtion and thus also contribute to the increased scattered radiation.

From Fig. 7 it can also be seen that the $R(M_1, M_2)$ factor is 0.347 for soot particles and 0.0417 for water particles. If the following quotients are setup:

$$\frac{R(M_1, M_2)_R}{R(M_1, M_2)_W} = \frac{0.347}{0.0417} = 8.33 \quad (21)$$

then it follows that with the same particle diameter and the same wavelength the scattering cross-section of soot is 8.33 times larger than the scattering cross-section of water (Eq. (20)). This factor is also again found in the graph shown in Fig. 4 in which the extinction cross-section (= scattering cross-section) of water droplets with a constant particle diameter runs parallel to the scattering cross-section of soot particles over the wavelength in the range of the Rayleigh approximation. However, it is smaller than the scattering cross-section of soot particles by just this factor of 8.33.

Conversely, this means that given the same diameter the concentration of water droplets must be 8.33 times greater than the concentration of soot particles in order to cause the same amount of deflection on a stray light meter or in a stray light detector given the same wavelength.

4. Examples of Applied Uses

In commercial extinction-measuring instruments which operate according to the double beam compensation process incandescent lamps are used for radiation sources and silicon photodiodes are used as radiation receptors. The wavelength of the test light is 0.8 μm.

It is possible to expand the use of an extinction-measuring instrument which can be used for determining wavelength exponents by adding, for example, a second radiation receptor and a separate measuring channel. If a lead sulfide photoconductor is used for the second measuring channel, then the radiation extinction in the region of $\lambda = 2\ \mu m$ can be measured. In this wavelength region the radiation source emits sufficient radiation. In this range window glass is still transparent for infrared radiation and the water vapor bands do not interfere with the measurement. To distinguish this additional test beam from the first test beam and from the reference beam the familiar methods of time, phase or frequency selection can be used in the electronic evaluation circuit.

In order to facilitate the numerical evaluation of the measurement it is suggested to digitize the test values of both channels, read them into a microcomputer via input gates and process them digitally. Setting up the quotient between the test beam and reference beam in both test channels, setting up the mean value with respect to time, calculating both extinction coefficients by taking the logarithm and standardizing on the test path distance and setting up the quotients between both extinction coefficients are algorithimic procedures which can be performed more elegantly, flexibly and efficiently on a microcomputer than by using analogous electronic modules. It /76 is also possible, using output gates from the computer, to check or control the lamp voltage, the switching of the effective range, the calculation and monitoring of limit values and for setting indicating instruments or alarms.

Setting up the quotient between the two test channels eliminates the particle concentration (Eq. (3)) and the extinction cross-section (or extinction effect factor) at wavelength λ_1 is divided by the extinction cross-section (or extinction effect factor) at wavelength λ_2. Referring to Fig. 4 this can be explained by means of an example.

Let it be assumed that the particles have a diameter of

$$d = \frac{1}{\pi}\ \mu m = 0.318\ \mu m$$

and that the wavelength of the test channels are $\lambda_1 = 0.8\ \mu m$ and $\lambda_2 = 2\ \mu m$. In this case, the abscissa scale for $1/\alpha$ agrees with the scale for λ.

If there are soot particles in the test path, then the upper curve in Fig. 4 with the equation

$$Q_{Ext}\left(\frac{\lambda}{\pi d}\right)_R = f\left(\frac{1}{\alpha}\right)$$

is valid. At λ_1 one reads $Q_{ExtR1} = 2.6$ and at λ_2 one reads $Q_{ExtR2} = 0.6$. From this the following quotient can be computed:

$$q_R = \frac{Q_{ExtR1}}{Q_{ExtR2}} = 4.33 \qquad (22)$$

For the wavelength exponent of the extinction cross-section for soot particles we obtain:

$$\eta_R = \frac{\log q_R}{\log(\lambda_1/\lambda_2)} = \frac{\log 4.33}{-\log(2/0.8)} = -1.6 \qquad (23)$$

If there are water droplets in the test path, then the lower curve in Fig. 4, with the equation

$$Q_{Ext}\left(\frac{\lambda}{\pi d}\right)_W = f\left(\frac{1}{\alpha}\right)$$

is valid. At λ_1 one reads $Q_{ExtW1} = 0.2$ and at λ_2 one reads $Q_{ExtW2} = 6.5 \cdot 10^{-3}$. Therefore we obtain

$$q_W = 30.8 \quad \text{and} \quad \eta_W = \frac{\log 30.8}{-\log(2/0.8)} = -3.74 \qquad (24)$$

It is a question for further analysis whether the quotients q or the wavelength exponents η are used to characterize the particles in the light path. In both cases, however, it is possible to distinguish between absorbent and transparent particles.

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