Dispersion composition of powdered coal particles

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The technique for measuring the size and identifying the shape of nonspherical particles of coarsely dispersed aerosol is reported. For particles of powdered coal is shown that the size spectrum of area- and perimeter-equivalent diameters d_s and d_p is well approximated by the lognormal distribution. However, the distribution parameters (d_{s50}, δ_{g_s}) and (d_{p50}, δ_{g_p}) differs, which indicates non-isomorphism of particle shapes. To identify a particle shape, the ratio of equivalent diameters ($\Delta = d_s/d_p$) is used: $\Delta = 1$ for spherical particles, its deviation from unit characterizes shapes of particle.

Introduction

Properties of aerosol particles strongly depend on their sizes and shapes.[1–3] The size of a spherical particle is uniquely determined by one parameter (radius or diameter). It is much more difficult to determine the size of a nonspherical particle. The most common approach to this problem now is the use of the notion of equivalent diameter. By definition, the equivalent diameter is the diameter of a spherical particle, properties of which coincide with those of a real particle. In measuring sizes of nonspherical particles with the characteristic sizes greater than 1–2 μm the optical microscopy[4] is widely used, which allows imaging of actual particles (flat or 3D). When the image is flat, two its parameters can be easily measured, i.e., perimeter and area, which allow then calculation of the equivalent particle diameters:

$$d_s(d_{1\text{eq}}) = \sqrt{4s/\pi} \text{ and } d_p(d_{2\text{eq}}) = p/\pi, \qquad (1)$$

where $d_{1\text{eq}}$ and $d_{2\text{eq}}$ are the area- and perimeter-equivalent particle diameters; s and p are the measured area and the perimeter of a particle.

For a spherical particle $d_{1\text{eq}} = d_{2\text{eq}}$ and $\Delta = d_{1\text{eq}}/d_{2\text{eq}} = 1$. The divergence of a particle from a spherical shape is characterizes by $\Delta < 1$.

The possibility to classify the shape of nonspherical particles by the value of Δ is analyzed in this paper by the example of powdered coal.

Preparation of a sample for microfilming and determining sizes of powered coal particles

The sample of powdered coal was given by the Laboratory of Ecological Problems of Heat-Power Engineering of the Institute of Thermophysics SB RAS. It was obtained through the coal grinding in a vibromill used to prepare the coal–water mixture. The characteristic sizes of powdered coal particles varied from 4 to 40 μm. For photographing, the powder was sprayed by a thin layer to a special glass covered with sticky lubricant. An Axioscop 2 plus optical microscope was used for imaging; the magnification was chosen depending on the size and properties of an object.[5]

To process images, the technique has been worked out realizable with the help of the MapInfo GIS.[6] The technique consists in a math transformation of a digital image, including the change from the pixel system to the Cartesian coordinate system, using the test object image and its scale. Then the object boundaries are outlined with a cursor in the interactive mode, thus fixing the discrete values of coordinates of the object points. Morphological parameters of the studied objects (the length of line segments, perimeters, areas) are computed with the standard MapInfo functions.

While further statistical processing of the results by Eq. (1), equivalent diameters are computed by areas and perimeters, as well as the distribution parameters of perimeter and area size spectra. The values are preserved in the tabular form and exported to Excel. For morphological classification, the results are statistically processed by matching the parameters of particles distribution over the values of equivalent diameter ratios ($\Delta = d_{1\text{eq}}/d_{2\text{eq}}$). The computation procedure was the following.

All the measured areas s_i and perimeters p_i of individual particles were ordered from minimal ($i = 1$) to maximal ($i_{\max} = n$); using these values and Eq. (1), the equivalent diameters d_{1i} and d_{2i}, as well as Δ_i were calculated for each particle. The values of Δ were also increasingly ordered from $\Delta_{\min}$ to $\Delta_{\max}$. To find the distribution functions of s, p, $d_{1\text{eq}}$, $d_{2\text{eq}}$, and Δ, lognormal approximation was used in the following form[17]:

$$\Phi(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} e^{-t^2/2}; \qquad (2)$$

$$t = \ln(x/x_{50})/\sigma, \quad \sigma = \ln\sigma_g, \qquad (3)$$

where y is the measured s and p, as well as d_1, d_2, and $\Delta = d_1/d_2$ calculated in terms of s and p; x_{50} are the median values of x; σ is the root-mean-square deviation of $\ln x$; σ_g is the x variance. The distribution parameters were obtained by the least squares method:

$$Y = a + bX, \tag{4}$$

$$Y_i = \Phi^{-1}(y_i),\ X_i = \ln(n_i/\Sigma n_i), \tag{5}$$

where $\Phi^{-1}(y_i)$ is the inverse to Eq. (2); y_i is the ith value of y; n_i is the sequence number of y_i.

The distribution parameters are calculated from the obtained a and b:

$$x_{50} = \exp(-a/b),\ \sigma_g = \exp(1/b). \tag{6}$$

The closeness of experimental data to the obtained distribution is characterized by the correlation coefficient r.

Table 1 presents the distribution parameters x_{50} and σ_g obtained with the least square method for the area, perimeter, equivalent diameters, and their ratio, as well as the coefficients of correlation between the lognormal approximation and the experimental data.

It is seen from Table 1 that the considered sequence of particle sizes is quite well described by the lognormal approximation (the coefficient of correlation is higher than 0.96). At the same time, the equivalent diameters calculated in terms of measured areas and perimeters of individual particles differ. The ratio of equivalent diameters for all the measured particles is less than unit, hence, shapes of powdered coal particles are nonspherical (Fig. 1a) and various. Since the size spectrum of the measured particles is quite properly approximated by the lognormal distribution, we compared the results of approximation in all 110 measured particles divided into 7 fractions with approximately equal number of particles in each fraction. Table 2 shows the determined distribution parameters for equivalent diameters and their ratios at different ways of sampling.

For comparison, the data for Δ are graphically shown in Fig. 2. Figure 2a shows the lognormal curve (*1*) describing the entire array of 110 measured particles (*2*). The similar approximating curve, plotted with the use of the data collection divided into 7 size fractions, is shown in Fig. 2b. The experimental points are closely spaced about the straight line independently of the division method. As is evident from Table 2, the parameters of curves in Figs. 2a and b coincide (x_{50}, σ_g, and r are equal).

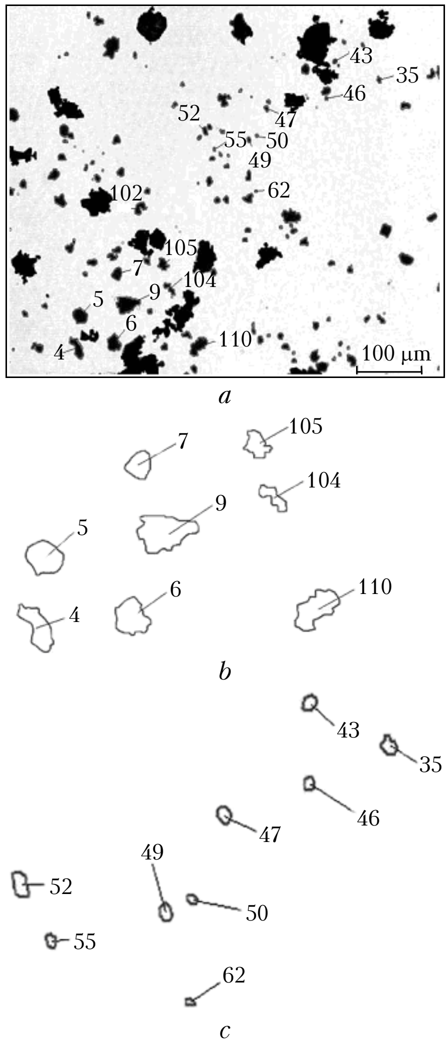

Fig. 1. Microview of powdered coal particles (a); shapes of particles with $\Delta < 0.88$ (b) and $\Delta > 0.88$ (c).

Table 1. Distribution parameters for the area, perimeter, equivalent diameters, and their ratios

s, μm^2			p, μm			d_1, μm			d_2, μm			$\Delta = d_1/d_2$		
s_{50}	σ_{g_s}	r_s	p_{50}	σ_{g_p}	r_p	$d_{1\,50}$	σ_{g_1}	r_1	$d_{2\,50}$	σ_{g_2}	r_2	Δ_{50}	σ_{g_1}	r_Δ
64.9	2.4	0.98	32.5	1.6	0.98	8.52	1.62	0.99	9.69	1.71	0.99	0.88	1.07	0.96
s_{min}	s_{max}	s_{max}/s_{min}	p_{min}	p_{max}	p_{max}/p_{min}	d_{1min}	d_{1max}	d_{1max}/d_{1min}	d_{2min}	d_{2max}	d_{2max}/d_{2min}	Δ_{min}	Δ_{min}	$\Delta_{max}/\Delta_{min}$
11	595	54	12	111	9	4	28	7	4	36	9	0.76	0.96	1.26

Table 2. Distribution parameters at different ways of sampling

N	d_{1eq}, μm			d_{2eq}, μm			Δ		
110	d_{50}	σ_{gd1}	r	d_{50}	σ_{gd2}	r	Δ_{50}	$\sigma_{g\Delta}$	r
	8.52	1.62	0.99	9.69	1.71	0.99	0.88	1.07	0.96
7	d_{1eq}, μm			d_{2eq}, μm			Δ		
	d_{50}	σ_{gd1}	r	d_{50}	σ_{gd2}	r	Δ_{50}	$\sigma_{g\Delta}$	r
	8.81	1.53	0.99	9.69	1.71	0.99	0.87	1.06	0.96

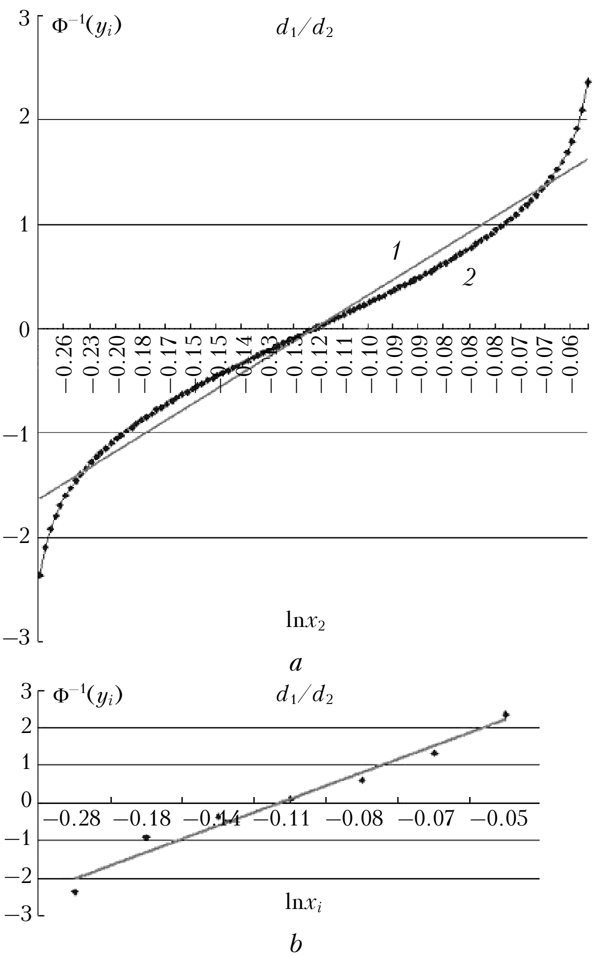

Fig. 2. Approximating curves for lognormal distribution of Δ for the entire array of particles (*a*) and 7 size fractions (*b*).

Thus, the comparison has shown that Δ can be used for shape classification of nonspherical particles. So, the particle array was divided into 6 groups; the lognormal distribution parameters were determined for each group (fraction) by the above-described technique. The results are shown in Table 3.

Table 3. Parameters of the lognormal distribution of Δ changes for 6 fractions

Fraction No.	$\Delta_{min}/\Delta_{max}$	n_i	Δ_{50}, μm	$\sigma_{g\Delta d}$	r
1	0.76/0.82	19	0.79	1.033	0.98
2	0.83/0.86	18	0.85	1.015	0.97
3	0.87/0.89	18	0.88	1.006	0.98
4	0.89/0.91	18	0.90	1.008	0.98
5	0.91/0.93	18	0.92	1.005	0.98
6	0.93/0.96	19	0.94	1.009	0.97

The degree of Δ change for each fraction is given in the second column; r is the coefficient of correlation between experimental values and the lognormal distribution approximating them.

The significant decrease of σ_g and the increase of the correlation coefficient when dividing into groups are evident from the comparison of Tables 2 and 3. By the Student criterion, each fraction with high probability differs from others in Δ (the Student criterion between ith and jth fractions $t_{ij} > 1.8$). The shapes of individual particles falling by the Δ value in two groups: (1) $\Delta < 0.88$ and (2) $\Delta > 0.88$ are shown in Figs. 1*b* and *c* with corresponding particle numbers. The individual value of Δ for each particle is given in Table 4.

Table 4

Particle No.	Δ_{50}	Particle No.	Δ_{50}
4	0.82	35	0.94
5	0.77	43	0.92
6	0.86	46	0.94
7	0.82	47	0.89
9	0.78	49	0.92
102	0.80	50	0.91
104	0.82	52	0.88
105	0.85	55	0.91
110	0.76	62	0.93

As is seen from Figs. 1*b* and *c*, the morphology of particles from the 1st group is quite various. The shapes of particles from the 2nd group ($\Delta > 0.88$) are close to spherical. Therefore, at $\Delta > 0.9$ the spherical shape of particles can be supposed. As for nonspherical particles with $\Delta < 0.8$, more detailed classification of particle shapes only by Δ is impossible today.

Based on the above-discussed, the following conclusions are drawn.

1. The size spectrum of nonspherical particles of powdered coal is properly approximated by the lognormal distribution of the measured areas s, perimeters p, equivalent diameters d_1 and d_2, and their ratios $\Delta = d_1/d_2$.

2. Particles with $\Delta > 0.9$ are close to spherical in their morphological characteristics.

3. The unique shape identification only by Δ is impossible for nonspherical particles at $\Delta < 0.9$.

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