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Study of Mechanisms of Grain Dust Explosion as Affected by Particle Size and Composition.
Part 2. Characterization of Particle Size and Composition of Grain Dust

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SUMMARY

Three types of grain dust (corn, wheat, and grain sorghum) and cornstarch (used as a reference) were each divided into varying size fractions (6 to 11) utilizing air and sieve classifications. The particle size distribution and the composition (content of moisture, ash, protein, and starch and fiber) of each size fraction were determined. Dust particles consisting almost entirely of ash material were found to concentrate in specific air-classified size fractions. The total external surface area, the total volume, and the coefficient of variability were calculated from the experimental particle size distribution for each size fraction by utilizing a piecewise log normal approximation. These values were compared with those calculated from the least-squares fitted log normal approximation of the actual distribution.

INTRODUCTION

A dust explosion is the rapid combustion of a solid reactant in the form of fine particles. Thus, the size and composition of the dust particles are important parameters in defining the reaction. Much has been postulated in the literature about the relationship of particle size and composition to a dust explosion, and some studies have been performed on various types of dust. However, little has actually been done to study either the explosibility of the different size ranges of particles or the composition of a specific type of grain dust.

In order to study the explosibility of grain dust in relation to particle size and composition, and the effect of these parameters on minimum explosible concentration, maximum explosion pressure, maximum rate of pressure rise, and average rate of pressure rise, it is necessary to first characterize the particle size and composition of grain dust. Studying the effect of particle size requires the use of a sample with the narrowest possible particle size distribution. Studying the effect of composition requires that moisture, ash, protein, and starch and fiber contents be known for each sample. This paper discusses theoretical particle size distribution, and describes the collection of dust samples, the separation of each sample into size fractions, the determination of the particle size distribution of each fraction, the calculation of the average particle diameter of each distribution, and the determination of the composition of each fraction. Dust samples of corn, wheat, and grain sorghum collected from cyclone dust control systems in commercial elevators were tested, and a commercial grade cornstarch was used as a reference.

THEORETICAL DETERMINATION OF PARTICLE SIZE DISTRIBUTION

Mass mean diameter

Two properties of the mass mean diameter D_m render it a convenient choice for describing the average particle diameter of grain dust. The first is that one-half of the total mass of the sample is contained in particles with diameters less than the mass mean diameter.

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The second is that the mass mean diameter approaches the geometric mean diameter based on weight $D_{g,3}$ and the geometric standard deviation $\sigma_{g,3}$ [1].

The mass mean diameter is determined from the cumulative weight distribution. Particle size distributions obtained from air and sieve classifications are typically log normal with varying degrees of distortion at the upper and lower ends of the distribution. This distortion depends on the precision of the classification. Typically there exists an interval about the cumulative weight percent of 50 that is log normal. Therefore, all of the data in this interval can be utilized in determining the mass mean diameter. However, the interval must contain at least two data points of which one is above a cumulative weight percent of 50 and the other below.

To determine the interval about the cumulative weight percent of 50 that is log normal, the following transformation is introduced:

$$w = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Z} \exp\left(-\frac{1}{2}x^2\right) \mathrm{d}x \tag{1}$$

where w is the cumulative weight percent and Z is the standard normal deviation.

In the case the data in the interval under consideration are from a log normal distribution, we have

$$Z = \frac{1}{\ln \sigma_{g,3}} \ln D - \frac{\ln D_{g,3}}{\ln \sigma_{g,3}} \tag{2}$$

where D is the particle diameter, $D_{g,3}$ is the geometric mean diameter for a log normal distribution based on weight (the mass mean diameter D_m) and $\sigma_{g,3}$ is the standard deviation for a log normal distribution based on weight.

To determine if the data in the interval under consideration are from a log normal distribution, we established a criterion based on the 95% confidence interval for the population correlation coefficient. The confidence interval had to contain 0.99; however, the lower boundary could not be less than 0.95.

Mean diameter based on external surface area

The mean diameter based on the external surface area $D_{a,2}$ is defined by Herdan *et al.* [2] as

$$D_{a,2} = \left[\frac{1}{\pi N_{tot}} \int_0^{\infty} \pi D^2 n(D)\, \mathrm{d}D\right]^{1/2} \tag{3}$$

where N_{tot} is the total number of particles in the sample and $n(D)$ is the particle size number distribution with diameter D as the distributed variable.

$D_{a,2}$ is equivalent to the diameter of the particle in a monodispersed particulate system that has the same total external surface area A_{tot} as that of a particulate system with a particle size distribution $n(D)$. In other words,

$$A_{tot} = N_{tot}(\pi D_{a,2}^2) = \int_0^{\infty} \pi D^2 n(D)\, \mathrm{d}D \tag{4}$$

Herdan *et al.* [2] have integrated eqn. (3) by assuming $n(D)$ to be a log normal distribution and obtained

$$D_{a,2} = D_{g,3} \exp(-2 \ln^2 \sigma_{g,3}) \tag{5}$$

To calculate $D_{a,2}$ for a non-log normal distribution, the 'piecewise log normal approximation' was applied by assuming that log normality exists between two adjacent data points (see Fig. 1). The distribution function of the fraction of the total mass contained in particles of diameter D, $w(D)$, is then given by

$$w(D) = \{w_i(D), i = 1, 2, \ldots, m-1\} \tag{6}$$

where

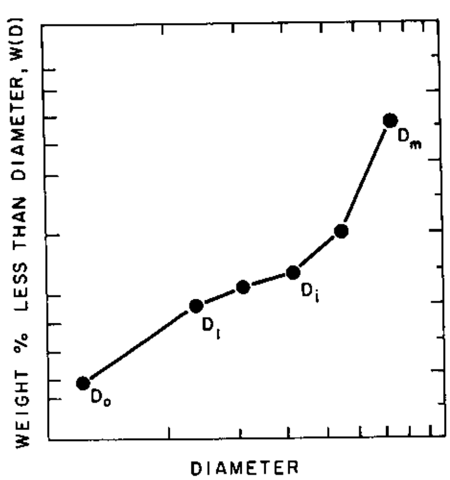

Fig. 1. Piecewise log normal approximation of the particle size distribution.

$$w_i(D) = \frac{1}{\ln \sigma_{g,3,i}(\sqrt{2\pi})} \exp -\frac{\ln^2\left(\frac{D}{D_{g,3,i}}\right)}{2 \ln^2\sigma_{g,3,i}} \frac{1}{D}$$

$$D_i \leqslant D \leqslant D_{i+1}$$

and m is the total number of data points.

From eqn. (3) we obtain

$$D_{a,2} = \left[\frac{\sum_{i=1}^{m-1} \frac{\exp\left(\frac{1}{2} \ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}} [\mathrm{erf}(y_{i+1}) - \mathrm{erf}(y_i)]}{\sum_{i=1}^{m-1} \frac{\exp \frac{9}{2}\left(\ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}} [\mathrm{erf}(x_{i+1}) - \mathrm{erf}(x_i)]}\right]^{1/2} \quad (7)$$

where

$$x_n = \frac{\ln\left(\frac{D_n}{D_{g,3,i}}\right)}{\sqrt{2} \ln \sigma_{g,3,i}} + 3 \frac{\ln \sigma_{g,3,i}}{\sqrt{2}} \qquad n = i, i+1$$

$$y_n = \frac{\ln\left(\frac{D}{D_{g,3,i}}\right)}{\sqrt{2} \ln \sigma_{g,3,i}} + \frac{\ln \sigma_{g,3,i}}{\sqrt{2}} \qquad n = i, i+1$$

As the entire distribution approaches a log normal distribution, the geometric mean $D_{g,3,i}$ and the geometric standard deviation $\sigma_{g,3,i}$ of each log normal section in eqn. (7) reduce, respectively, to $D_{g,3}$ and $\sigma_{g,3}$, which are common for the entire distribution. The resultant expression is

$$D_{a,2} = D_{g,3} \exp(-2 \ln^2\sigma_{g,3}) \times \times \left[\frac{\mathrm{erf}(y_m) - \mathrm{erf}(y_1)}{\mathrm{erf}(x_m) - \mathrm{erf}(x_1)}\right]^{1/2} \quad (8)$$

In addition, the maximum diameter D_{max} and the minimum diameter D_{min} of the distribution will approach infinity and zero respectively. This causes y_m and x_m to approach positive infinity and y_1 and x_1 to approach negative infinity. This gives, from eqn. (8),

$$D_{a,2} = D_{g,3} \exp(-2 \ln^2\sigma_{g,3})\left[\frac{1-(-1)}{1-(-1)}\right]^{1/2} \quad (9)$$

or

$$D_{a,2} = D_{g,3} \exp(-2 \ln^2\sigma_{g,3}) \quad (10)$$

Mean diameter based on mass

The mean diameter based on mass $D_{a,3}$ is

$$D_{a,3} = \left[\frac{6}{\rho_d \pi N_{tot}} \int_0^\infty \frac{\pi}{6} \rho_d D^3 n(D)\, dD\right]^{1/3} \quad (11)$$

$D_{a,3}$ can be interpreted as the effective diameter of the particles in the monodispersed system that has the same total mass M_{tot} as the actual particulate system with a particle size distribution of $n(D)$. Note that

$$M_{tot} = \int_0^\infty \frac{\pi}{6} \rho_d D^3 n(D)\, dD = \frac{\pi}{6} \rho_d (D_{g,3})^3 N_{tot} \quad (12)$$

Herdan *et al.* [2] have integrated eqn. (11) for a log normal distribution and obtained

$$D_{a,3} = D_{g,3} \exp[-1.5 \ln^2\sigma_{g,3}] \quad (13)$$

Again the assumption is made that the non-log normal type of distribution can be approximated by a distribution that is log normal between two adjacent data points (see Fig. 1). Substitution of the relation for $n(D)\, dD$ in eqn. (3) into eqn. (11) yields

$$D_{a,3} = \left\{\frac{\sum_{i=1}^{m-1} [\mathrm{erf}(Z_{i+1}) - \mathrm{erf}(Z_i)]}{\sum_{i=1}^{m-1} \frac{\exp\left[\frac{9}{2} \ln^2\sigma_{g,3,i}\right]}{D_{g,3,i}{}^3} [\mathrm{erf}(x_{i+1}) - \mathrm{erf}(x_i)]}\right\}^{1/3} \quad (14)$$

where

$$Z_n = \frac{\ln\left(\frac{D}{D_{g,3,i}}\right)}{\sqrt{2} \ln \sigma_{g,3,i}} \qquad n = i, i+1$$

As the entire distribution approaches a log normal distribution, or as

$$D_{g,3,i} \longrightarrow D_{g,3}$$

$$\sigma_{g,3,i} \longrightarrow \sigma_{g,3}$$

eqn. (14) is transformed into

$$D_{a,3} = D_{g,3} \exp(-1.5 \ln^2\sigma_{g,3}) \times \times \left[\frac{\mathrm{erf}(Z_m) - \mathrm{erf}(Z_1)}{\mathrm{erf}(x_m) - \mathrm{erf}(x_1)}\right]^{1/3} \quad (15)$$

Furthermore, as log normality is approached, we obtain

$D_m \longrightarrow \infty$

$D_1 \longrightarrow 0$

which cause

$Z_m, x_m \longrightarrow \infty$

$Z_1, x_1 \longrightarrow -\infty$

Thus, eqn. (15) becomes

$$D_{a,3} = D_{g,3} \exp(-1.5 \ln^2\sigma_{g,3}) \tag{16}$$

Note that eqn. (16) is identical to eqn. (13).

Coefficient of variability

The coefficient of variability, C.V., is calculated from each distribution. It is a measure of the variability of particle diameters in the distribution about its mean and is defined as

$$\text{C.V.} = \frac{\left[\int_0^\infty (D - \bar{D})^2 \frac{n(D)}{N_{tot}} \, dD\right]^{1/2}}{\bar{D}} \tag{17}$$

where

$$\bar{D} = \int_0^\infty D \frac{n(D)}{N_{tot}} \, dD$$

$$\bar{D} = \int_0^\infty D \frac{n(D)}{N_{tot}} \, dD \qquad \text{(the arithmetic mean diameter)}$$

Finney [1] has shown that when $n(d)$ is log normally distributed, the coefficient of variability is

$$\text{C.V.} = [\exp(\ln^2\sigma_{g,3}) - 1]^{1/2} \tag{18}$$

When the distribution is approximated by a piecewise log normal distribution (Fig. 1), it can be shown that the coefficient of variability is

$$\text{C.V.} = \left\{ \frac{\left[\sum_{i=1}^{m-1} \frac{\exp\left(\frac{9}{2} \ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}^3} [\text{erf}(x_{i+1}) - \text{erf}(x_i)]\right]\left[\sum_{i=1}^{m-1} \frac{\exp\left(\frac{1}{2} \ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}} [\text{erf}(y_{i+1}) - \text{erf}(y_i)]\right]}{\left[\sum_{i=1}^{m-1} \frac{\exp(2 \ln^2\sigma_{g,3,i})}{D_{g,3,i}^2} [\text{erf}(w_{i+1}) - \text{erf}(w_i)]\right]} - 1 \right\} \tag{19}$$

MATERIALS AND METHODS

Collection of dust samples

Dust samples from corn, wheat, and grain sorghum were collected from storage bins of dust removal systems as well as from several other locations in each of three commercial grain elevators. The wheat dust and corn dust samples were collected from systems that employed cyclones to separate dust from air, and the grain sorghum dust samples were collected from a system that used a baghouse to make the separation. Each sample was 2 to 3 kg in weight, and a sieve with a 1.0 mm mesh opening was used to remove very large 'trash'. One hundred pounds of cornstarch were obtained in bulk from a mill (General Mills, Minneapolis, MN).

Separation of dust samples into size fractions

A 250 Tyler mesh sieve was used to initially divide each dust sample into a coarse fraction (having particle diameters approximately greater than 61 μm) and a fine fraction. This separation was performed because the series 6000 Microparticle Classifier used to further separate the fine fraction of each sample could not effectively classify grain dust particles with diameters larger than 61 μm.

The series 6000 Microparticle Classifier (manufactured by A.E. Bahco in Sweden and distributed by Harry W. Dietert Co., Detroit, MI) was employed to separate grain dust particles with diameter less than 61 μm. The classifier used the combined effects of centrifugation and elutriation to separate 0.02 kg of dust into a fine fraction and a coarse fraction. The dust particles were subjected to a centrifugal force which was opposed by a current of air. The fine fraction, composed of dust particles with a terminal velocity less than the air velocity, was blown into a collector. The remaining dust, the coarse fraction, was thrown by centrifugal force into another collector.

The fine fraction from the 250 Tyler mesh sieve of the wheat dust, corn dust, grain sorghum dust, or cornstarch was further separated into eight size fractions using the microparticle classifier. Size fractions were obtained by performing a series of separations, each with a progressively higher air velocity. The finest size fraction was first separated out of the entire fine fraction by the lowest air velocity. After increasing the air velocity, the next fraction was divided again into a fine fraction and a coarse fraction. This was repeated until eight size fractions were obtained; however, the three size fractions with the finest particles were combined into one because each individually did not provide enough material for an explosion test.

The coarse fraction from the 250 mesh sieving of each dust sample was also further divided into size fractions with a series of sieves having Tyler mesh numbers of 65, 115, 150, 170, and 200 (corresponding openings of 208, 124, 105, 88, and 74 μm). These six fractions were accumulated from 0.100 kg portions, which were sieved for 15 min on a Ro-Tap shaker (W. S. Tyler Company, Cleveland, OH). The fraction on top of the 65 mesh sieve was considered trash and discarded because it contained a wide range of particle sizes. Thus, each type of dust was separated into 11 size fractions by utilizing the same air velocities for air classification and the same series of sieves for sieve classification. Note that size fractions 1 through 6 were from the air classification and size fractions 7 through 11 were from the sieve classification. During sieve classification, a large degree of carry-over of particles with diameters smaller than the sieve apertures occurred unless the sieving was done carefully.

Determination of particle size distribution

The particle size distribution in each of the eleven size fractions was determined by the AACC method 50-10 [3], namely, the Whitby sedimentation method which classifies particle size hydrodynamically. By centrifugal sedimentation, dust is allowed to settle in a capillary tube filled with a liquid termed the sedimentation liquid. The diameter obtained corresponds to the diameter of a sphere that falls with the same velocity as the real particles. Though the physical dimension of the particles obtained by this method might be different from those of the real particles in many cases, the distribution is one for spheres that behave hydrodynamically and is obtained by measuring the cumulative volume of dust.

Benzene was used as the sedimentation liquid for the corn, grain sorghum, and wheat dust; isopropyl alcohol was used for the cornstarch. The dust was initially dispersed in a feed solution consisting of the sedimentation liquid and naptha, which was then placed on top of the sedimentation liquid in the tube. To decrease the settling time, the particles were centrifuged for increasing lengths of time at 600, 1200, and 1800 rpm.

The weight percent of the total dust sample that had settled out was determined by measuring the height of the settled dust column. The diameter of the largest particles that settled out was determined from the rpm of the centrifuge and the length of time the sample was centrifuged.

Determination of composition

The composition of each size fraction was characterized by determining its content of moisture, ash, protein, and starch and fiber. The weight fraction of moisture, ash, and protein was determined by the AACC methods 44-40, 08-01, and 46-10, respectively [3]. The weight fraction of starch and fiber was obtained from the difference.

RESULTS AND DISCUSSION

Particle size

Particle size distribution

The geometric mean diameter $D_{g,3}$ and the natural logarithm of the geometric standard deviation, $\ln \sigma_{g,3}$, of the log normal approximation of the actual particle size distribution for data with $|Z| < 2$ were calculated. The coefficient of determination R^2 and the 95% confidence interval for the population correlation coefficient ρ_r are also calculated (data not shown). Twenty-one of the 43 particle size distributions are not complete; they do not contain data at the two extreme cumulative weight percentages, 0% and 100%. However, 15 out of these 21 distributions are essentially complete because each of them spans more than 95% of the total range of cumulative weight percents. Five of the remaining incomplete distributions contain no data between the cumulative weight percents of 95% and 100%. Among these five distributions, four are from size fractions of grain sorghum dust with maximum cumulative weight percents of 93.5, 91.0, 76.5, and 48.0%, respectively, and one is from a size fraction of corn dust with a maximum cumulative weight percent of 84.2%. Only one contains no data with cumulative weight percents between 0% and 5%. This is from the size fraction of cornstarch having a minimum weight percent of 5.4%.

Data at the upper extreme of the distributions are missing because there exists in the Whitby sedimentation method a limit on the maximum particle diameter that can be measured accurately. The first cumulative weight percent measurement is recorded at the moment when particles with a diameter equal to the maximum diameter have settled to the bottom of the capillary tube. Particles with diameters larger than the maximum diameter will have already accumulated in the tube before the first reading, and this could result in the first cumulative weight percent reading of less than 100%.

In this case, it is more critical to have data in the lower, rather than upper, end of a weight distribution, because the number of particles per unit weight of dust is larger at the lower end of the distribution than at the upper end. All of the distributions, except for the size fraction of cornstarch, contain data with cumulative weight percents less than 14.0%.

The parameter of the log normal approximation for each distribution for data with values of $|Z| < 2$ was recorded. Only data with $|Z| > 2$ were discarded because the Whitby sedimentation method does not give accurate results for data in this region [4]. Note that only 16 of the 43 distributions are from size fractions that were sieve classified and the remainder are from size fractions that were air classified. The four sieve-classified size fractions are from corn dust. The twelve air-classified size fractions consist of two corn dust fractions, six cornstarch fractions, two wheat dust fractions, and two grain sorghum dust fractions. Four of the six fractions of cornstarch, whose size distributions are essentially log normal, were from non-freeze-dried samples (this is 2/3 of the total number of non-freeze-dried size fractions) and the remaining two are fractions that were freeze dried (this is 1/3 of the total number of freeze-dried size fractions). Figure 2 represents the particle size distribution of size fraction No. 4 of grain sorghum dust, Fig. 3, fraction No. 2 of cornstarch, and Fig. 4, fraction No. 1 of cornstarch by freeze drying. Notice that without freeze drying, cornstarch can be separated into fraction 1, since particles in the small fraction tend to agglomerate when freeze dried. After freeze drying, starch granules were broken up as indicated in Fig. 4. The diameter is plotted on a logarithmic axis, and the cumulative weight

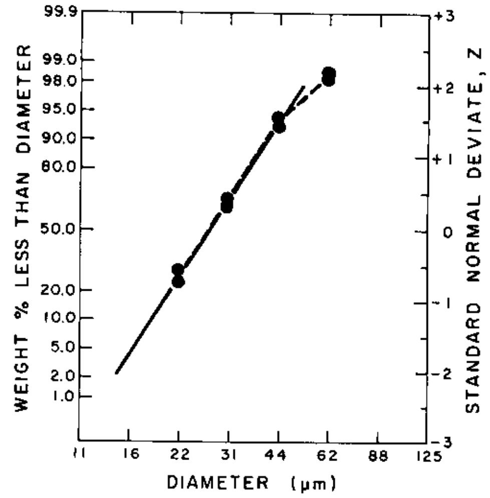

Fig. 2. Particle size distribution of grain sorghum dust.

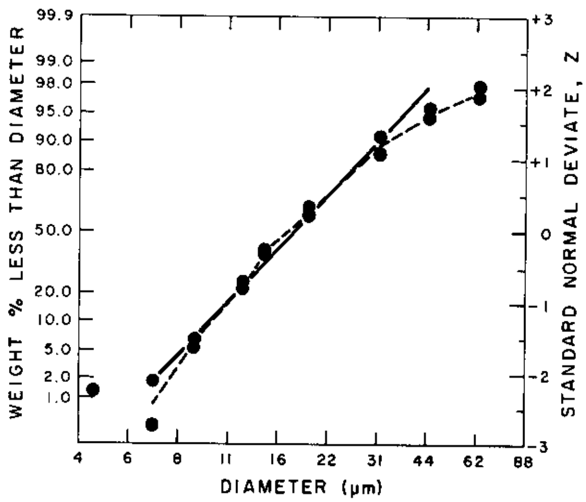

Fig. 3. Particle size distribution of cornstarch.

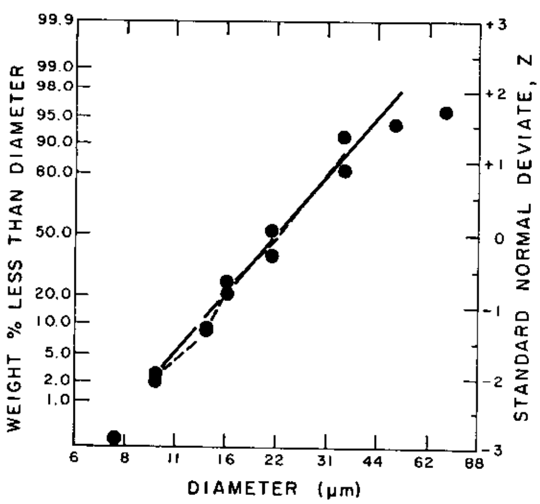

Fig. 4. Particle size distribution of freeze-dried cornstarch.

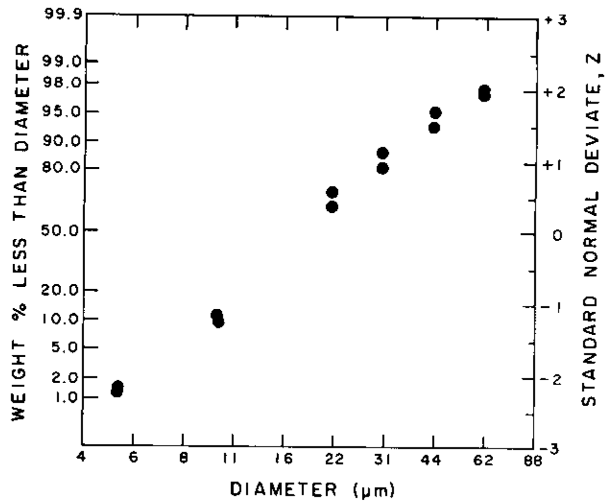

Fig. 5. Particle size distribution of corn dust.

percent on a probability axis. The cumulative weight percent is also presented in terms of the standard normal deviation.

Even though the particle size distribution of the original samples of corn dust, wheat dust, grain sorghum dust, and cornstarch are approximately log normal (Figs. 2 - 5), the particle size distributions of the size fractions from the sieve and air classifications are not necessarily log normal. Herdan *et al.* [2] have illustrated the shape of the resultant size distributions from perfect air and sieve classifications (see Fig. 2). Notice that there exists a range of cumulative weight percents W around the cumulative weight percent of 50%, where the distribution of particle diameters is log normal, *i.e.*, the slope of the line tangent to the distribution is constant; however, outside this range, the slope of the tangent line increases toward infinity as the values of W approach 0% at the diameter of $D_{\min}$ and 100% at the diameter of $D_{\max}$.

The shapes of the distributions in Figs. 2 - 4 are different from that in Fig. 5. The distributions in Figs. 2 - 4 can be divided into two categories. The first category contains those distributions that are log normal for the entire range of particle diameters: the slope of the line tangent to the distributions is constant. The second category contains those distributions in which, at the lower end, the slope of the tangent line first decreases toward zero as the particle size increases, and then increases toward a constant value. As the particle size further increases toward the upper end, the slope decreases and then

TABLE 1

Amount of weight in particles with diameters less than the lower boundary sieve apertures

Size fraction	Sieve aperture d_a (μm)	Stokes equivalent diameter of d_a, d_s (μm)	Weight percent less than d_s		
			Grain sorghum dust (wt.%)	Wheat dust (wt.%)	Corn dust (wt.%)
7	61	55	60	92	95
8	74	67	62	88	98
9	88	79	80	99	98
10	105	95	> 70	100	> 84
11	124	112	> 50		> 84

TABLE 2

Amount of weight in particles with diameters greater than the upper boundary sieve apertures

Size fraction	Sieve aperture d_a (μm)	Stokes equivalent diameter of d_a, d_s (μm)	Weight percent less than d_s		
			Grain sorghum dust (wt.%)	Wheat dust (wt.%)	Corn dust (wt.%)
7	74	67	18	3	2
8	88	79	15	5	0.5
9	105	95	< 10	< 0.01	< 2
10	124	112	< 20	< 0.01	< 16
11	208	188			< 16

increases again. The shape of the lower portion of the distribution is the result of a range of diameters for a relatively large number of particles. Correspondingly, the shape of the upper portion of the distribution is the result of a range of diameters with relatively small number of particles followed by a range of larger diameters for a relatively large number of particles.

The deviations from the shape predicted by Herdan *et al.* [2] in the upper end of the distribution in Figs. 2 - 4 are more pronounced for the air-classified size fractions than for the sieve-classified fractions. The deviations in the lower region of the distribution are more pronounced for the sieve-classified size fractions than for the air-classified size fractions except for the fifth air-classified size fraction. Also, the deviations that occur in the corn dust size fractions are less than those in the wheat and the grain sorghum dust size fractions.

When particles are sized by sieving, the range of particles with diameters in each size fraction should fall within the apertures of the bounding sieves. Therefore, the weight of particles with diameters less than the lower boundary sieve aperture and the weight of particles with diameters larger than the upper boundary sieve aperture can be estimated. However, to compare methods of sizing particles, the shape of the particles should be considered. Irani and Callis [5] have reported the value of the shape factor relating the sieve aperture to a stokes diameter to be approximately 0.9. Sieve openings, transformed to equivalent stokes diameters utilizing this shape factor, are shown in Tables 1 and 2. For each sieve-classified size fraction, Table 1 gives the lower boundary sieve aperture, d_a^L, used to obtain the size fraction and the equivalent stokes diameter, d_s^L, of the aperture; the value of d_s^L was obtained with the use of the shape factor of 0.9 [5]. In addition, the fraction of the total weight of dust in the size fraction that is contained in particles with diameters less than d_s^L is given. In Table 2, the aperture of the upper boundary sieve d_a^U of each size fraction is given with its equivalent stokes diameter d_s^U. The fraction of the total weight of dust in the size fraction contained in particles with diameters greater than d_s^U is also presented. Note that the fraction of the total weight of the dust

TABLE 3

Results from an analysis of variance of the coefficients of variability for size fractions

Source of variation	Degrees of freedom	Sum of squares	Mean square	F
Treatment				
Dust	2	2194.26	1097.13	60.41*
Size fraction	9	4823.30	535.92	29.51*
Interactions				
D × S	18	6508.23	361.57	19.91*
Error	30	544.94	18.16	
Total	59	14070.73		

*Significant at the 1% level.

ranges from 80% to 100% in a size fraction that is contained in particles with diameters less than the stokes equivalent diameter of the lower sieve aperture. However, the fraction of the total weight of the dust ranges from only 0.01% to 20% in the size fraction that is contained in particles with diameters larger than the stokes equivalent diameter of the upper boundary sieve aperture.

Small balls of particles could be seen in the size fractions of wheat dust and grain sorghum dust. Martin [6] found that wheat dust contains particles called tricombs which range from 50 to 200 μm in length and 10 to 30 μm in diameter, and which have a large length to diameter ratio in the range of 5 to 10. These tricombs can trap large quantities of small particles during the sieving operation and prevent them from passing through the sieve. Martin [6] also found that grain sorghum dust contains hair-like projections. During the sieving operation, these projections can capture small diameter particles to form a ball that cannot pass through the sieve.

The coefficients of variability range from 22% for the air-classified size fraction of grain sorghum dust to 104% for the freeze-dried size fraction of cornstarch. When examining the hypothesis that the size fractions are monodispersed, the smallest coefficient of variability, 22%, is relatively large; a value of 10% is the generally accepted level of variability in an experiment.

To ascertain if there were any significant differences between the values of the coefficient of variability for the different types of dust or for different size fractions, a two-way analysis of variance for a 2 × 2 fractional experiment was used in which the treatments were the type of dust and the size fraction.

The results in Table 3 show that significant differences at the 1% level do exist both among the types of dust and among the size fractions; however, the interactions are also significant at the 1% level. The significant interactions indicate that the type of dust has different effects on the coefficients of variability for various size fractions. Also, the effect that the size fraction has on the coefficient of variability is not the same for every type of dust. However, a difference can still exist between air-classified size fractions and sieve-classified size fractions. Figure 6 shows that the values of the coefficient of variability for all the air-classified size fractions, except for wheat dust, are consistently lower than those for the sieve-classified size fractions.

Figure 7 presents the expected particle size distributions from the perfect sieve or air classification of a sample of dust originally having a log normal particle size distribution, curve A. Three types of classification are presented:

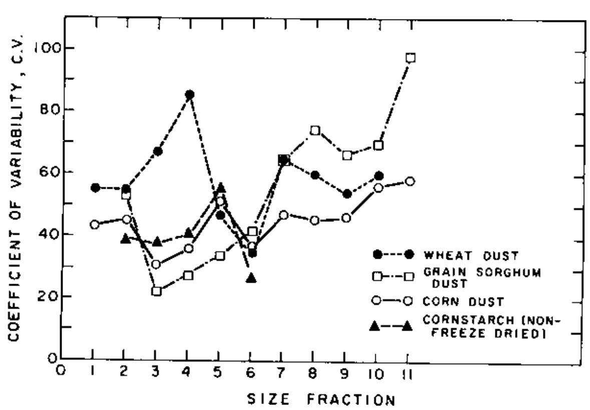

Fig. 6. Correlation between the coefficient of variability and the size fraction.

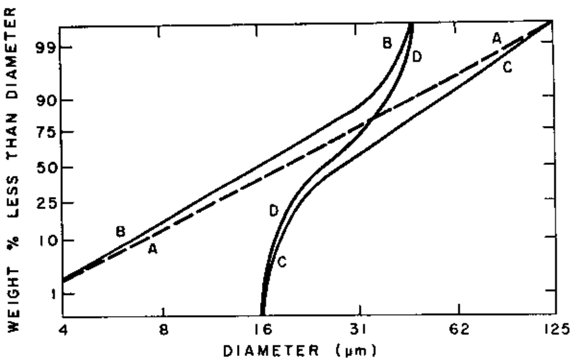

Fig. 7. Particle size distribution expected from perfect air or sieve classification of a dust with a log normal particle size distribution A [2].

a) particles with diameters less than D_{min} are removed, curve B,
b) particles with diameters greater than D_{max} are removed, curve C, and
c) both a) and b) are performed, curve D.

Mass mean diameter

The mass mean diameter D_m of each distribution, along with the natural logarithm of the geometric standard deviation, ln σ_g, of the log normal distribution used in determining the mass mean diameters were calculated. The coefficient of determination of the distribution and the 95% confidence interval for the population correlation coefficient p_r were also calculated (data not shown). Thirteen of the mass mean diameters are from distributions which are sufficiently non-log normal that only two pairs of data points (each pair consisting of two repetitions) could be used in determining the mass mean diameter. In Table 4, for each sieve-separated size fraction, the apertures of the bounding sieves with their geometric mean are presented. In addition, the equivalent stokes diameter was determined with the use of a shape factor of 0.9 [5]. The mass mean diameters and geometric mean diameter of each size fraction of the three types of dust samples are compared in Table 4. For each type of dust, the mass mean diameters of the air-classified size fractions increase with the size fraction as expected; however, the sieve-classified size fractions do not. Table 4 shows the mass mean diameters to be consistently lower than the geometric average of the bounding sieve apertures, corrected for particle shape effects. This is expected due to the large number of particles with diameters less than the lower boundary sieve aperture.

Mean diameter based on external surface area

To calculate the average diameter based on external surface area, $D_{a,2}$, from the piecewise log normal approximation of the actual distribution, a complete distribution is necessary. Nineteen of the 43 distributions do not contain cumulative weight percent data at the upper extreme of 100%. For these distributions, the log normal distribution through the two largest data points was used to estimate the actual distribution in the region having no data. Four of the 43 distributions do not have data at the lower extreme of 0%. For these distributions, a log normal distribution which contained the data with the smallest cumulative weight percent and had a geometric standard deviation σ_g equal to that of the log normal approximation of the entire distribution was used to estimate the actual distribution in the region where there are no data.

The values of $D_{a,2}$ from two log normal approximations of the actual particle size

TABLE 4

Comparison of the geometric mean diameter of the boundary sieve apertures to mass mean diameters

Size fraction	Sieve aperture		Geometric mean of sieve aperture d_a (μm)	Stokes equivalent diameter of d_a (μm)	Weight percent less than d_s		
	Lower (μm)	Upper (μm)			Grain sorghum dust (wt.%)	Wheat dust (wt.%)	Corn dust wt.%)
7	61	74	67	60	50	34	24
8	74	88	81	73	63	36	24
9	88	105	96	86	64	31	26
10	105	124	114	103	72	32	34
11	124	208	161	145	89	—	60

distribution and one piecewise log normal approximation of the actual distribution were calculated for each size fraction of each type of dust. One log normal approximation was determined with only those data having $|Z| < 2$ and the other data having $|Z| < 3$. The coefficients of variability between each log normal approximation and the piecewise log normal approximation were calculated. The data show differences between values of $D_{a,2}$, calculated by approximating the actual distribution with a log normal distribution and with a piecewise log normal distribution. For 15 size fractions, the coefficient of variability is greater than 10% when only data with values of $|Z| < 2$ are considered in the determination of the log normal approximation. When the log normal approximation is determined using data with $|Z| < 3$, only eight size fractions have coefficients of variability larger than 10%. This indicates that the extreme lower parts of the distribution with $Z < -2$ can be important in the calculation of $D_{a,2}$; it contains a large fraction of the total number of dust particles in the size fraction. When the estimate of $D_{a,2}$ from the log normal approximation is larger than that from the piecewise log normal approximation, the log normal approximation underestimates consistently the weight percents of the fine particles. When the estimate of $D_{a,2}$ from the log normal approximation is lower than that from the piecewise log normal approximation, the log normal approximation overestimates consistently the cumulative weight percents of the fine particles.

The differences between the value of $D_{a,2}$ calculated from the piecewise log normal distribution and that from each of the log normal distributions can be attributed to differences in calculating the quantity N_{tot}/W_{tot}. It can be shown that

$$D_{a,2} = \left(\frac{\sum_{i=1}^{m-1} \frac{\exp\left(\frac{1}{2}\ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}} [\operatorname{erf}(y_{i+1}) - \operatorname{erf}(y_i)]}{\sum_{i=1}^{m-1} \frac{\exp\left(\frac{9}{2}\ln^2\sigma_{g,3,i}\right)}{D_{g,3,i}} [\operatorname{erf}(x_{i+1}) - \operatorname{erf}(x_i)]} \right)^{1/2} \tag{20}$$

Note that the right-hand side of the above equation does not contain the quantity N_{tot}/W_{tot}. The values of the quantity on the left-hand side of eqn. (20) were calculated from a log normal approximation of the actual particle size distribution and from the piecewise log normal approximation of each size fraction. The coefficient of variability between the value of $D_{a,2}{}^2(N_{tot}/W_{tot})(6/\pi\rho_d)$ calculated from the piecewise log normal distribution, and that from the log normal distribution determined from data with $|Z| < 2$ for each size fraction, were also calculated for each size fraction. Note that none of the coefficients of variability are greater than 10% and only two are greater than 5%.

Mean diameter based on mass

The values of $D_{a,3}$ from two log normal approximations of the actual particle size distribution and one piecewise log normal distribution were calculated for each size fraction. These two log normal approximations are the same as those used for determining $D_{a,2}$. The coefficients of variability between the value of $D_{a,3}$ from each log normal approximation and that from the piecewise log normal approximation were calculated as are the values of the average diameter based on the mass. In calculating $D_{a,3}$ for an incomplete distribution, the same methods were used as those employed in the calculation of $D_{a,2}$. The differences between the value of $D_{a,3}$ from each log normal approximation and that from the piecewise log normal approximation are similar to those previously noted for values of $D_{a,2}$. The coefficients of variability for $D_{a,3}$ are not so large as those for $D_{a,2}$; the calculation of $D_{a,3}$ involves the cubic root of N_{tot}/W_{tot} as opposed to the square root in the calculation of $D_{a,2}$. The cubic root reduces the effect of the differences in N_{tot}/W_{tot} more than the square root does.

A comparison between the mass mean diameter D_m in Table 1 and the values of $D_{a,3}$ for the same size fraction indicate that 19 of the pairs differ only by 5 μm; however, the remaining differ as much as 68 μm. Furthermore, even when two size fractions have the same mass mean diameter, they can have substantially different values of $D_{a,3}$. The mass mean diameter indicates that one-half of the weight of the sample is in particles with diameters less than D_m; however, it contains no information on how the weight is distributed among the particles. The mass mean diameter does not characterize the particle size distribution sufficiently because two particulate systems can have appreciably different particle size distributions and yet have identical mass mean diameters. This difficulty is a feature of any geometric mean diameter. The geometric diameter is only one of two parameters necessary to characterize a log normal distribution. Two different log normal distributions can have the same geometric mean diameters D_m and yet can have different geometric standard deviations σ_g.

Composition

The weight percents of moisture, ash, protein, and starch and fiber for each size fraction are presented in Table 5. The starch

TABLE 5

Composition of each size fraction

Identification number	Moisture	Weight percent (wt.%)		Starch and Fiber
		Ash	Protein	
CNAC-S01	11.7	2.20	6.7	79.40
CNAC-S02	12.1	1.31	4.8	81.79
CNAC-S03	12.1	1.35	4.6	81.95
CNAC-S04	11.9	6.43	6.9	74.77
CNAC-S05	11.3	14.13	8.5	66.07
CNAC-S06	7.3	46.27	6.1	40.33
CNAC-S07	12.4	3.94	7.7	75.96
CNAC-S08	12.6	3.37	6.9	77.13
CNAC-S09	12.5	3.25	6.8	77.45
CNAC-S10	12.6	3.39	7.5	76.51
CNAC-S11	12.5	3.84	8.4	75.26
WTAC-S01	10.4	5.19	6.7	77.71
WTAC-S02	11.8	9.06	12.1	67.04
WTAC-S03	11.0	6.97	8.5	73.53
WTAC-S04	9.0	14.96	11.1	64.94
WTAC-S05	8.8	24.99	12.7	53.51
WTAC-S06	6.8	44.83	14.0	34.37
WTAC-S07	10.6	6.79	11.9	70.71
WTAC-S08	10.8	5.95	9.4	73.85
WTAC-S09	10.3	5.24	6.3	78.16
MOAC-S01	10.0	7.14	10.0	72.86
MOAC-S02	10.3	5.14	6.5	78.06
MOAC-S03	11.4	4.49	4.3	79.81
MOAC-S04	10.1	11.74	6.0	72.16
MOAC-S05	10.2	22.78	8.7	58.32
MOAC-S06	7.7	30.09	8.3	44.91
MOAC-S07	11.1	9.73	9.7	69.47
MOAC-S08	11.6	6.25	8.1	74.05
MOAC-S09	12.0	5.52	7.3	75.18
MOAC-S10	12.1	5.82	7.3	74.78
CSAC-S02	11.3	0.00	0.0	88.70
CSAC-S03	10.6	0.00	0.0	89.40
CSAC-S04	9.9	0.00	0.0	90.10
CSAC-S05	8.9	0.00	0.0	91.10
CSAC-S06	9.0	0.00	0.0	91.00
CSAC-F01	4.0	0.00	0.0	96.00
CSAC-F02	4.0	0.00	0.0	96.00
CSAC-F03	14.9	0.00	0.0	85.10
CSAC-F04	12.2	0.00	0.0	87.80
CSAC-F05	12.1	0.00	0.0	87.90

TABLE 6

Mean, standard deviation, and coefficient of variability of moisture, ash, protein, or starch and fiber content among the size fractions within each dust

Composition component	Sample identification	Number of samples	Mean, $\bar{x}$ (%)	Standard deviation (%)	Coefficient of variability (%)
Moisture	Wheat	9	9.9	1.5	15
	Grain sorghum	11	10.8	1.3	12
	Corn	11	11.7	1.5	13
	Cornstarch	9	9.9	3.4	34
Ash	Wheat	9	13.8	13.3	97
	Grain sorghum	11	11.4	10.6	93
	Corn	11	8.1	13.1	162
Protein	Wheat	9	10.3	2.7	26
	Grain sorghum	11	7.8	1.8	23
	Corn	11	6.8	1.3	19
Starch and fiber	Wheat	9	66.0	14.1	21
	Grain sorghum	11	70.0	10.0	14
	Corn	11	73.3	11.7	16
	Cornstarch	9	90.1	3.4	4

and fiber content was obtained by subtracting the sum of the weight percents of moisture, ash, and protein from 100%, since the dust was assumed to contain only those components.

Table 6 shows the average values of moisture, ash, protein, and starch and fiber content for each dust. The standard deviation of the content of each component among the size fractions of each kind of dust is also given as well as the coefficient of variability of each component. The standard deviations of protein content among the size fractions of each test dust range from 1.3% to 2.7% and those for the moisture content from 1.3% to 1.5%. This indicates that the protein content and the moisture content vary only slightly among the size fractions of the same type of dust. The standard deviation of 3.4% for moisture content among the size fractions of cornstarch indicates that their variability is larger than those of other types of dust. The larger variability for cornstarch is the result of freeze drying some of the size fractions to improve their dispersibility.

The ash content and the starch and fiber content of each type of dust show more variability between size fractions than do the moisture and the protein content. The standard deviations of the ash content among size fractions of each type of dust range from 10.6% to 18.3% and those for the starch and fiber content from 10.0% to 14.6%. The standard deviation of the starch and fiber content in cornstarch, 3.4%, is less than that for the other kinds of dust. In contrast, the standard deviation of 2.8% among the average values of the ash content for wheat dust, grain sorghum dust, and corn dust, and that of 3.7% for the starch and fiber content indicate only a slight variability among the dust types.

Table 7 contains the average values of all types of dust, the standard deviation among these average values, and the coefficient of variability among these average values for each component. The standard deviation of the average value for the moisture content of all dust samples is 1.8% and that for protein content is 0.9%. The variability of protein content and moisture content among the different kinds of dust is approximately the same as or smaller than the variability among size fractions within each kind of dust.

In Fig. 8, the moisture content of each test dust is plotted against the size fraction. The results correlating ash, protein, and starch and fiber content with size fraction are presented in Figs. 9 - 11.

Martin and Lai [7] have shown that air classification of grain dust results in a large ash content (approximately 40%) in the residue size fraction. Figure 9 indicates a similar trend in ash content for the size

TABLE 7

Mean, standard deviation, and coefficient of variability of moisture, ash, protein, or starch and fiber content among the average values for each dust

Composition component	Number of samples	Mean, $\bar{x}$ (%)	Standard deviation (%)	Coefficient of variability (%)
Moisture	4	10.6	0.86	8
Ash	5	11.1	2.84	26
Protein	3	8.3	1.80	22
Starch and fiber	4	75.0	10.60	14

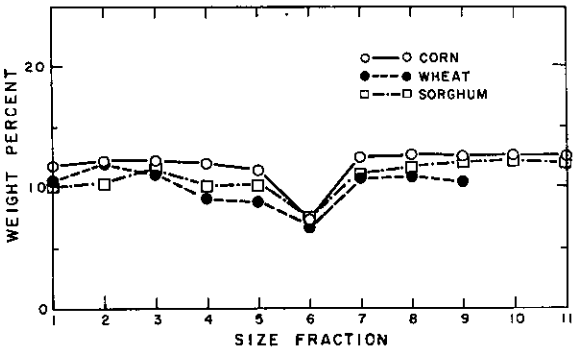

Fig. 8. Comparison of the moisture content of each size fraction.

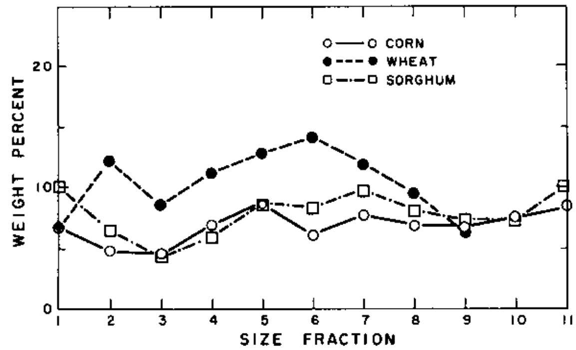

Fig. 10. Comparison of the protein content of each size fraction.

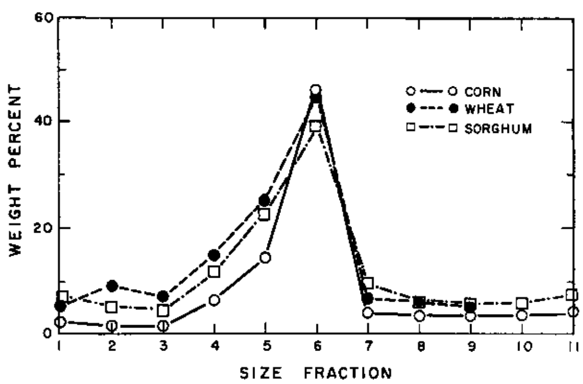

Fig. 9. Comparison of the ash content of each size fraction.

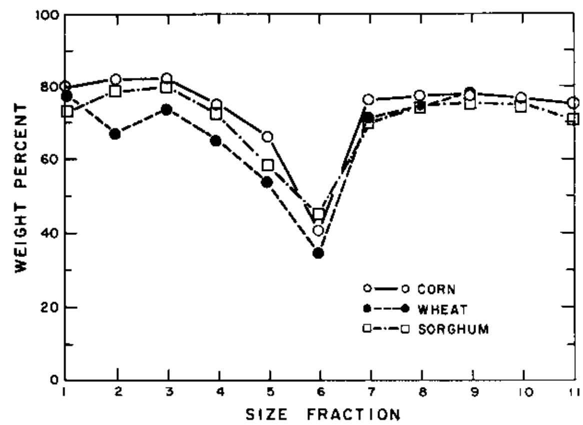

Fig. 11. Comparison of the starch and fiber content of each size fraction.

fractions in this investigation; the residue size fractions correspond to the sixth size fraction. The fifth size fraction of each dust contains large weight percentages of ash (approximately 25%). For the wheat dust and the grain sorghum dust, the fourth size fraction also contains a relatively large ash content (approximately 11%) when compared with the ash content of the remaining size fractions (approximately 4%).

In Figs. 8 and 11, a similar trend is noted for the moisture content and for the starch and fiber content. For these two quantities, the fourth, fifth, and sixth size fractions exhibit lower values than those of the remaining size fractions. The correlation coefficients between the ash content and each of those quantities are significant at the 1% level (Table 8). Table 8 contains the standard deviations of compositional content among the size fractions of each test dust that results when the data from size fractions 6, 5, and 4 are removed one at a time. The highly significant inverse correlation between the ash and

TABLE 8

Simple correlation coefficients for the correlation between compositional components

Correlation	Correlation coefficients, r			
	Grain sorghum dust	Wheat dust	Corn dust	Cornstarch
Ash and moisture	−0.83**	−0.91**	−0.97**	—
Ash and starch and fiber	−0.98**	−0.99**	−0.99**	—
Moisture and starch and fiber	0.76**	0.85**	0.94**	1.0**
Protein and ash	—	0.72*	—	—
Protein and starch and fiber	—	−0.82**	—	—

*Significant at the 5% level.
**Significant at the 1% level.

TABLE 9

Effect of removing separation numbers 4, 5, and 6 in the standard deviation of the composition components among the size fractions for each type of grain dust

Composition component	Type of dust	Number of samples	Sample removed			
			none	6	6, 5	6, 5, 4
Moisture	Wheat	9	1.51	1.0	0.8	0.5
	Grain sorghum	11	1.30	0.8	0.8	0.8
	Corn	11	1.53	0.4	0.3	0.3
	Means		0.80	0.9	0.8	0.8
Ash	Wheat	9	13.32	6.9	3.4	1.4
	Grain sorghum	11	10.60	5.5	2.3	1.6
	Corn	11	13.14	3.7	1.6	1.1
	Means		2.84	2.6	2.4	2.1
Protein	Wheat	9	2.70	2.5	2.4	2.5
	Grain sorghum	11	1.80	1.9	2.0	2.0
	Corn	11	1.27	1.3	1.3	1.3
	Means		1.80	1.5	1.4	1.3
Starch and fiber	Wheat	9	14.10	8.1	5.0	4.2
	Grain sorghum	11	10.00	5.9	3.3	3.4
	Corn	11	11.74	4.5	2.7	2.6
	Means		3.70	3.4	2.8	2.5

moisture content results from the ash material being less hygroscopic than the organic grain dust. The correlations between the starch and fiber content and the ash content are significant.

The large standard deviations of the ash content and the starch and fiber content among the size fractions of each test dust have resulted from the large ash content in size fractions 4, 5, and 6. The standard deviations of the compositional contents of the remaining size fractions are given in Table 9. For all three types of dust, the standard deviations of the ash content decrease to less than 2%, and those of the starch and fiber content to 4.2%. For the moisture content, the standard deviations decrease to less than 1%. The standard deviations of the protein content among the size fractions exhibit essentially no change.

The correlation coefficients in Table 8 indicate three additional significant correlations. The correlation between the moisture content and the starch and fiber content is significant for all types of dust at the 1% level. The correlation between the protein content and either the ash content or the starch and fiber content is significant for only the wheat dust at the 5% level. The correlation between the moisture content and the starch and fiber content is the result of the difference between the moisture content and the ash content and that between the ash content and the starch and fiber content.

The partial correlation coefficient of −0.70 with the effect of ash removed between the moisture content and the starch and fiber content indicates no significant correlation at the 5% level.

Correlation between particle size and composition

The contention that composition is dependent on particle diameter was not verified for particle diameters ranging from 10 to 90 μm. The correlation coefficients between each of the compositional components and the mass mean diameter indicate that it is significant at the 5% level for all types of dust except wheat dust. The correlation coefficient between the mass mean diameter and the moisture content is −0.74, and that between the mass mean diameter and the ash content is 0.673. Both are significant at the 5% level. Figure 6 indicates that the correlation between mass mean diameter and ash content is significant only for wheat dust; by coincidence, those size fractions (4, 5, and 6) which have the highest ash content due to air classification also have the largest mass mean diameters. The same observation was not made for grain sorghum dust or corn dust. Therefore, the correlations for grain sorghum dust and corn dust are not significant at the 5% level. For wheat dust, the sieve-separated size fractions do not have the largest mass mean diameters because they contain a large number of relatively small diameter particles. This results in size fractions 4, 5, and 6, by coincidence, having the largest mass mean diameters. The high ash content of size fractions 4, 5, and 6 indicates that most of the ash is contained in separate particles consisting entirely of ash and not in particles of grain dust. The ash particles are either distributed in a narrow size range (approximately 40 to 60 μm) or they are of higher density than the grain dust particles. The ash content of grain dust does not depend on the size of the particle.

The significant correlation between moisture content and mass mean diameter of wheat dust is due to the significant correlation between moisture content and ash content, as discussed previously. The wheat dust size fractions that contain the lowest moisture content also contain the highest ash content and happen to have the largest mass mean diameters. Again, grain sorghum dust and corn dust do not exhibit these trends.

CONCLUSIONS

Wheat dust, corn dust, and grain sorghum dust were similar in composition and in range of particle diameters. The ash content and starch and fiber content of each type of dust showed more variability between size fractions than did the moisture content and protein content. The correlation coefficients between each of the compositional components and the mass mean diameter indicated that it was significant at the 5% level for all types of dust except wheat dust.

For complete derivation details of the equations in this paper, please contact Dr. F. S. Lai.

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REFERENCES

1 D. J. Finney, *J. Royal Statistical Society, Vol. VII, Suppl. No. 2* (1941).
2 G. Herdan, M. L. Smith and W. H. Hardwick, *Small Particle Statistics*, Butterworth, London, 1960.
3 American Association of Cereal Chemists, *Approved methods of the AACC*, The Association, St. Paul, MI, 12th edn., 1979.
4 C. R. Martin, personal communication, 1980.
5 H. Heywood, *Proc. Symposium on Particle Size Analysis, London, 1947.*
6 C. R. Martin, *Characterization of grain dust properties*, Paper No. 78-3020, American Society of Agricultural Engineers, 1978.
7 C. R. Martin and F. S. Lai, 1979, *Physical and chemical composition of grain dust*, Paper No. 79-3090, American Society of Agricultural Engineers, 1979.