In Situ Measurement of Grain Dust Particle Size Distribution and Concentration

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ABSTRACT

A light extinction method for determining the *in situ* particle size distribution and concentration of grain dust that is suspended in a grain bin is presented. The particle size distribution was determined by analyzing the change in light attenuated as particles settled out of the dust cloud. The steady state particle size distribution before the onset of settling was assumed to be equal to the values determined by settling. The steady state dust mass concentration before the onset of settling was then calculated from the value of light attenuation and the particle size distribution at several locations in a grain bin using the light extinction-settling method. A high volume air sampler was also used to measure the dust mass concentration. Dust that settled onto a horizontal surface was collected and its particle size was measured. These measurements were made as the bin was filled with corn and wheat at two grain flow rates.

INTRODUCTION

The concentration of grain dust evolved from grain during its handling can be measured optically. However, it is necessary to know the particle size distribution of the particles in the cloud. The first objective of our paper is to present a method of measuring the particle size distribution of particles in a dust cloud by using the temporal variation of light attenuation of a settling cloud. The second objective is to predict the mass concentration by using the measured size distribution and the value of the light attenuation at the beginning of settling.

Hertzberg et al. (1979) measured the light attenuated by the dust cloud in a dust explosion test apparatus, but they did not measure the temporal variation of the settling cloud. Chang et al. (1980) used light extinction to measure the qualitative difference in optical density (the logarithm of the inverse of light transmission) of a grain dust cloud created by a grain spreader in a corn bin. Martin et al. (1980) found that the light attenuated by a dust cloud could be related to the dust concentration in a corn bin as measured by a high volume air sampler; however, since they treated their data purely empirically their resultant correlation was only applicable to a specific grain type (wheat or corn) and grade (sample grade or No. 1 grade). Aldis et al. (1980) developed a method of determining the particle size distribution of grain dust by measuring the temporal variation of light attenuated by a settling dust cloud. They calculated a dust cloud concentration using this measured particle size and the optical density of the dust cloud. A description of their method is presented in this paper in a later section.

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Measurement of Particle Size Distribution

Methods for measuring the size distribution of particles dispersed in a dust cloud are classified as a sampling method or an *in situ* method. A sampling method requires the extraction from the dust cloud of a sample, which is analyzed outside of the dust cloud. For an *in situ* method the measurement is made within the dust cloud without changing the airflow pattern of the cloud.

Sampling methods: Several methods of measuring the particle size distribution involve sampling the dust cloud (Orr, 1978). Some of these methods are mechanical sieving, filtering, cascade impacting, volumetric measure by electrical resistance (Coulter counter), particle cross-sectional area (HIAC), and volumetric measurement of the accumulated dust separated by selective settling (Whitby, 1955).

Removing a sample from the dust cloud in order to measure the particle size distribution of the dust may change the airflow patterns. In addition, the extracted dust sample must be redispersed to measure the particle size. In some of the methods, e.g., sieving, the particles are separated as they are sized, but in others like those used by the Coulter counter or HIAC instruments the dust samples are redispersed in a liquid before they are sized. When the dust is redispersed in a liquid, the particle size distribution may be altered because of surface static charges, or greater shearing forces.

***In situ* methods:** Available *in situ* methods for measuring the particle size distribution are not as numerous as the sampling methods. The two methods presently available are the light scattering method (Shifrin and Kolmakov, 1967; Swithenbank et al., 1977; Cornillault, 1972; Felton, 1978; Held et al., 1979; Caroon and Borman, 1979) and the light attenuation-dust settling method (Sinclair, 1950; and Rose, 1954).

The *in situ* methods have several advantages over the sampling methods. Since a dust sample is not extracted from the dust cloud, the cloud is not disturbed. The optical devices presently available (Microtrac by Leeds and Northrope, Malvern instruments, and Held et al., 1979) produce a complete particle size distribution in a few minutes. The instruments developed by Malvern and Held et al., (1979) have the potential of being able to record the data necessary for the calculation of a particle size distribution in less than 1 m.

The disadvantage of most of the light scattering methods is that they require both a laser light source and a computer. Since the intensity of the scattered light is a fraction of the light emitted from the light source, a very intense source is required. After the data are obtained, a matrix inversion (Swithenbank et al., 1977) a curve fitting procedure (Felton, 1978), or an integral transformation (Held et al., 1979) is performed on a computer.

The light attenuation-dust settling methods developed by Aldis et al. (1980) and described in this paper use the measured variation of light intensity of unscattered light, so an intense light source, i.e., a laser, is not necessary. Aldis et al. (1980) found that the particle size distribution may be obtained from the data without the use of a computer if the distance from the ceiling of the dust cloud container is less than 0.5 m. They have also determined that Stoke's law appeared to be valid for the terminal velocity of the particles in the dust clouds they examined and that the effect of a nonhorizontal dust cloud container ceiling can be accounted for by using an arithmetic average value of the distance from the ceiling to the horizontal light path.

Measurement of Dust Concentration

Methods of measuring dust concentration are also classified as sampling methods or *in situ* methods (Orr, 1978).

Sampling methods: One of the sampling methods for measuring dust concentration is the high volume filter method, where dust laden air is passed through a filter which removes the dust from the air. The dust concentration is calculated by dividing the weight of dust collected on the filter by the volume of air that has been passed through the filter. Since a cumulative weight of dust is captured by the filter, dust concentrations obtained by this method are averaged over the collection period. The accuracy of the filter method of measuring dust concentration is dependent on the accuracy of the airflow measurement. (Normally an air velocity can only be measured to within about 10% of the true value). Filter methods will, in addition, cause a change in the air flow pattern of the dust cloud (as referred to in the earlier section on the measurement of the dust particle size distribution).

***In situ* methods:** The concentration of dust in a dust cloud can be measured *in situ* by measuring the light attenuated by the dust cloud if both the particle size distribution of the dust and the extinction coefficient are known (Lee et al., 1980). If a particle size distribution of the dust in a dust cloud is constant, then the light scattered or attenuated by the cloud will be proportional to the dust concentration (Hertzberg et al., 1979; Lee et al., 1980; Schmitt, 1979; and Shofner et al., 1979).

DERIVATION OF THE MODEL

Fundamental Equation

The continuity equation for particles moving through still air is (Friedlander, 1977)

$$\frac{\partial n}{\partial t} = \nabla \cdot D \nabla n - \nabla \cdot Vn \quad [1]$$

where

n = $(d_p, \underline{x}, t)$ = particle density distribution

t = time

D = diffusion coefficient of the particles in air

V = migration velocity of the particles

$\underline{x}$ = position vector.

It is assumed that the effects of particle diffusion, electrical fields, thermophoresis and other force fields are insignificant with respect to gravity and that the migration velocity is not a function of position. Then, we have

$$\frac{\partial n}{\partial t} = -V \frac{\partial n}{\partial x} \quad [2]$$

where x is the coordinate in the direction of the gravitation field. Consider the case where dust is suspended in a semi-infinite enclosure with the top of the enclosure at $x = 0$ and where

$$n(d_p, x0) = n_o(d_p, x) \text{ for } x > 0,$$

$$n(d_p, x, 0) = 0 \text{ for } x \leqslant 0, \text{ and}$$

d_p = particle diameter.

The solution to equation [2] with the initial conditions above is obtained as (see e.g., Zachmanoglou and Thoe, 1976)

$$n(d_p, x, t) = u(x-Vt)\, n_o\, (d_p, x-Vt) \quad [3]$$

where

$u(x\text{-}Vt) = 1$ for $(x\text{-}Vt) > 0$

$= 0$ for $(x\text{-}Vt) \leqslant 0$.

The particle volumetric size distribution for grain dust has been found to be approximately log normal by Martin (1981). A log-normal particle number distribution can be expressed as

$$f_o\,(d_p) = \frac{\exp\left\{-\left[\frac{\ln\left(\frac{d_p}{d_g}\right)}{\sqrt{2}\ln\sigma_g}\right]^2\right\}}{\sqrt{2\pi}\, d_p} \quad [4]$$

where

d_g = geometric number mean particle size,

σ_g = geometric standard deviation, which is assumed to be independent of position d_p.

The cross-sectional area of dust particles per unit volume, $A(x,t)$ may be obtained from $n(d_p,x,t)$ and we can calculate light attenuation from the Bouguer-Beer-Lambert Law as shown below.

$$\ln \frac{1}{T(x,t)} = \int_o^L K\, A(x,t)\, dz \quad [5]$$

where

T = light transmission through the dust cloud

z = coordinate in the direction of the light receiver from the light source

K = light extinction coefficient

L = length of light path through dust cloud.

For dust particles with diameters much greater than the wave length of light the extinction coefficient is constant at approximately 2.0 (Friedlander, 1977).

Now let us consider attenuation of a light beam passing through a dust cloud inside a closed vessel. In general both the particle size and number density will vary vertically. In addition the ceiling of the vessel may not be parallel to the light beam path. Therefore, the relevant vertical coordinate is the distance from the ceiling of the enclosure which can be expressed as a function of the distance from the light beam emitter to the sensor. Equations [3] and [5] can be obtained to give

$$\phi(x,t) = \frac{\ln[\frac{1}{T[x(z),t]}]}{\ln[\frac{1}{T[x(z),0]}]} = \frac{\int_0^L \int_0^\infty u[x(z)-vt]\; c[x(z)-yt]\, d_p{}^2 f(d_p,x(z),t)\; d(d_p)dz}{\int_0^L \int_0^\infty c[x(z)]\; d_p{}^2\; f_o[d_p,x(z)]\; d(d_p)\; dz} \quad \ldots [6]$$

where

$f(d_p,x,t) = f_o(d_p,x\text{-}Vt)$
$n_o(d_p,x) = c(x)\, f_o(d_p,x)$
$c(x)$ = initial particle number density
z = distance from the sensor along the light path
σ = optical density ratio.

By using equation [4] for the particle size distribution we obtain

$$\phi(x,t) = \frac{\int_0^L \int_0^\infty \frac{u[x(z)-vt]\; c[x(z)-vt]\; d_p{}^2}{[d_p\sqrt{2\pi}\ln\sigma_g} \exp\left\{\left[\frac{\ln \frac{d_p}{d_g[x(z)-vt]}}{\sqrt{2}\ln\sigma_g}\right]\right\}^2 d(d_p)dz}{\int_0^L \int_0^\infty \frac{c[x(z)]\; d_p{}^2}{(d_p\sqrt{2\pi}\ln\sigma_g)}\left\{\exp - \left[\frac{\ln \frac{d_p}{d_g[x(z)-vt]}}{\sqrt{2}\ln\sigma_g}\right]^2\right\} d(d_p)dz} \quad \ldots [7]$$

Since in general it may not be possible to integrate equation [7] without resorting to numerical methods, we shall make some simplifying assumptions that will allow the evaluation of the integrals.

Ideal Settling in a Stagnant Cloud

To simplify equation [7], several assumptions are made. The first is that the initial particle number density and the geometric number mean particle size are not functions of the vertical distance from the ceiling of the dust cloud container. The second is that the ceiling of the dust cloud container is parallel to the horizontal light beam that is attenuated by the dust in the cloud. The third that the particle velocity can be calculated from the Stoke's law. Under these assumptions equations [7] can be simplified to

$$\phi(x,t) = \frac{\int_0^\infty u \quad x - \frac{d_p{}^2 t}{k^2} \quad d_p \exp\left\{-\left[\frac{\ln(\frac{d_p}{d_g})}{\sqrt{2}\ln\sigma_g}\right]^2\right\} d(d_p)}{\int_0^\infty d_p \exp\left\{-\left[\frac{\ln(\frac{d_p}{d_g})}{\sqrt{2}\ln\sigma_g}\right]^2\right\} d(d_p)}$$

where

k = $(18\mu^{1/2}/g\rho_p)$
μ = viscosity coefficient of air
g = gravitational acceleration
ρ_p = particle mass density, 1.5 g/cm^3

The solution to the above equation is

$$\phi(x,t) = \frac{\operatorname{erf}\left[\dfrac{\ln \dfrac{k(\frac{x}{t})^{1/2}}{d_g}}{\sqrt{2}\ln \sigma_g} - \sqrt{2}\ln \sigma_g\right] + 1}{2}$$

. . . . [8]

Initial Number Density as a Function of Vertical Distance

When the particle number density is a linear function of vertical distance, then $\phi(x,t)$ is

$$\phi(x,t) = \frac{\int_0^\infty u\left(x - \frac{d_p^2 t}{k^2}\right)\left[a\left(x - \frac{d_p^2 t}{k^2}\right) + b\right] d_p \exp\left\{-\left[\frac{\ln(\frac{d_p}{d_g})}{\sqrt{2}\ln\sigma_g}\right]^2\right\} d(d_p)}{\int_0^\infty [ax+b]\, d_p \exp\left\{-\left[\frac{\ln(\frac{d_p}{d_g})}{\sqrt{2}\ln\sigma_g}\right]^2\right\} d(d_p)}$$

. . . . [9]

where

b = particle number density at x = 0

a = slope of the particle number density versus vertical position.

The solution of equation [9] is

$$\phi(x,t) = \frac{\operatorname{erf}\left[\dfrac{\ln\left[\dfrac{k(\frac{x}{t})^{1/2}}{d_g}\right]}{\sqrt{2}\ln\sigma_g} - \sqrt{2}\ln\sigma_g\right] + 1}{2}$$

$$- \frac{d_g^2 t}{2k^2 [x + \frac{b}{a}]} [\exp(6\ln^2\sigma_g)\Big\{\operatorname{erf}\left[\frac{\ln\ k(\frac{x}{t})^{1/2}}{\sqrt{2}\ln\sigma_g} - 2\sqrt{2}\ln\sigma_g\right] + 1\Big\}]$$

. . . . [10]

Prediction of Particle Size Distribution

In the derivation of the method of predicting the particle size distribution from light extinction measurements during settling, the following assumptions are made. The ceiling is assumed to be parallel to the horizontal light beam. The Stoke's law is assumed to be valid. The particle number density and the particle size are assumed to be linear functions of the vertical distance from the dust cloud container ceiling according to the following linear expressions.

$C(x) = a\ x + b$ and . . . . [11]

$d_g = (\frac{3}{2})\ a_1\ x + b_1$ . . . . [12]

The area ratio, $\phi(x,t)$, as a function of time, is predicted by equation [10].

The method used in this work to predict area ratio consisted of fitting equation [10] to an experimental light extinction-curve by eye. The two parameters in equation [11] appear in equation [10] as the ratio b to a, and therefore, the ratio of these two parameters was adjusted. g_g in equation [10] was calculated from equation [12] by adjusting a_1 and b_1.

Prediction of Dust Cloud Concentration

The concentration of dust in a cloud can be predicted if we know the geometric mass mean particle size of dust suspended in the cloud, the geometric standard deviation, the light path length through which the attenuation occurs, and the extinction coefficient. The following equation can be used to predict the mass concentration (e.g. Hertzberg et al., 1979).

$$C_m = \left(\frac{2 \rho_p d^3_{a,3}}{3 \; L \; K \; d^2_{a,2}} \right) \ln \left(\frac{1}{T}\right) \quad \ldots\ldots\ldots\ldots [13]$$

where

$d_{a,2}$ = arithmetic area mean particle size of the suspended dust

$d_{a,3}$ = arithmetic volume mean particle size of the suspended dust,

ρ_p = true dust particle density

C_m = dust mass concentration.

The ratio of the arithmetic mean particle sizes can be calculated from

$$\frac{d^3_{a,3}}{d^2_{a,2}} = d_{g,3} \exp \; -0.5 \ln^2 \sigma_g \quad \ldots\ldots\ldots\ldots [14]$$

where

$d_{g,3}$ = geometric mass mean particle size

EXPERIMENTS

The light attenuated by a settling grain dust cloud in a grain bin was measured in this study. The grain bin had a side wall height of 5.0 m (18 ft) and a diameter of 6.4 m (21 ft). The grain dust clouds were created by sample grade yellow dent corn and hard red winter wheat as it fell into the bin through an orifice. The moisture content of the corn was 12.5% and the broken kernels and foreign material content was greater than 7%. Wheat was No.1 grade at 12.5% moisture content. This wheat had many previous handlings whereby the dust removed by the dust control system was not returned to the grain. The test number, grain flow rate and orifice diameter are listed in Table 1.

The light attenuated by the dust cloud was measured by a device developed by Lee et al. (1979) and modified by Martin et al. (1980). The device consists of light-emitting diode (LED, Texas Instruments TIL-31)* and a phototransistor (PT, Texas Instrument TIL-81) mounted 1 m apart in a rigid aluminum frame. The voltage across the PT was then measured and recorded by an Esterline Angus PD 2064 recorder. Three identical light attenuation measurement devices were placed in the grain bin at 45.7, 228.6 and 381 cm from the ceiling of the bin. The light path was horizontal to the bin floor, approximately 20 cm from the bin wall and parallel to a chord.

The phototransistors used in this study were calibrated by measuring the voltage across the PT as neutral density filters were placed in the light path between the LED and the PT. The light transmitted by the neutral density filters had been previously measured with a spectrophotometer at the wave length of the light emitted by the LED. It was found that the variation of light transmission was a linear function of voltage drop across the PT ($R^2 = 0.98$ with 5 degrees of freedom). Thus, the voltage measurements could be used directly to obtain the ratio of the light attenuation at a time to the light attenuation at the beginning of settling.

The following procedure was used to measure the light attenuation in the grain bin. First, corn was dropped into the grain bin for approximately 10 min. After the grain flow stopped the light attenuation was monitored for an additional 30 min.

In addition to the light attenuation measurements two types of dust samples were taken from the dust cloud in the grain bin. A high volume filter with no cover was located 3 m from the bin ceiling and approximately 56 cm from the bin wall. Air was pulled through the filter at a flow rate of 0.0132 m^3/sec (28 cfm) for 20 minutes beginning when the grain flow started. Dust samples were also collected from three 15.2 cm by 15 cm cardboard settling plates. Each settling place was located under the light attenuation devices prior to the initiation of the test, and was removed after completion of the test. The dust collected on each plate was weighted and the particle size distribution for the dust was determined by using a Whitby particle size analyzer. Dust density was measured with a Bechman air pycnometer.

The particle size distribution of dust that was collected from the high volume filter was measured with a Whitby particle size analyzer. This sedimentation method developed by Whitby (1955) and employed extensively by Martin et al. (1978) on grain dust was used, with isopropyl alcohol as the sedimentation fluid.

RESULTS AND DISCUSSION

The results of the experiments are presented in Fig. 1 through 6 and Tables 1 through 4. The optical density of the dust clouds is presented as a function of time in Fig. 1 through 4. The normalized optical density ratio of the settling dust cloud is presented versus time in Fig. 5 and 6. The test conditions in the 8 tests are shown in Table 1. In Table 2 the parameters used to produce the predicted attenuation-settling curves found in Fig. 5 and 6 are

TABLE 1. EXPERIMENTAL CONDITIONS USED IN TESTS 1 THROUGH 8

Test	Grain	Orifice dia. cm	Flow rate, t/h
1	Corn	15.75	36.44
2	Corn	15.75	39.37
3	Corn	19.30	74.66
4	Corn	17.40	76.21
5	Wheat	18.19	79.76
6	Wheat	18.19	81.29
7	Wheat	15.75	42.32
8	Wheat	15.75	42.35

*Reference to company or product does not imply approval or recommendation of the product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

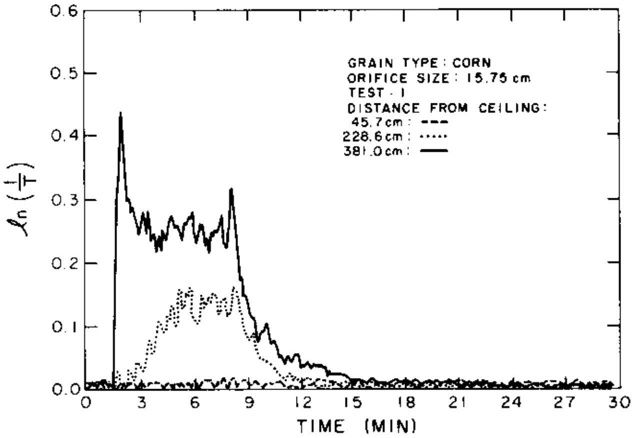

Fig. 1—Light attenuated by a dust cloud created by grain falling into a grain bin - Test 1.

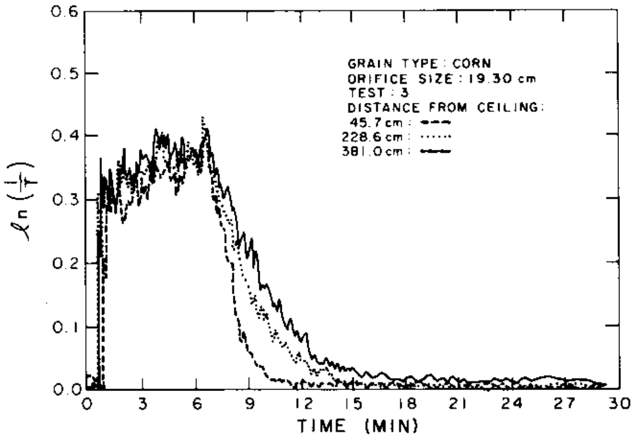

Fig. 2—Light attenuated by a dust cloud created by grain falling into a grain bin - Test 3.

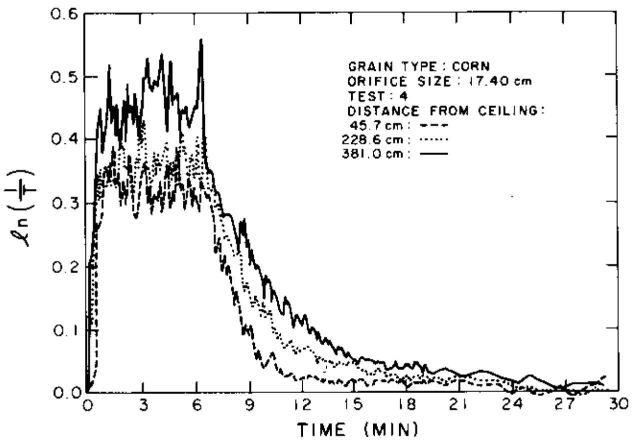

Fig. 3—Light attenuated by a dust cloud created by grain falling into a grain bin - Test 4.

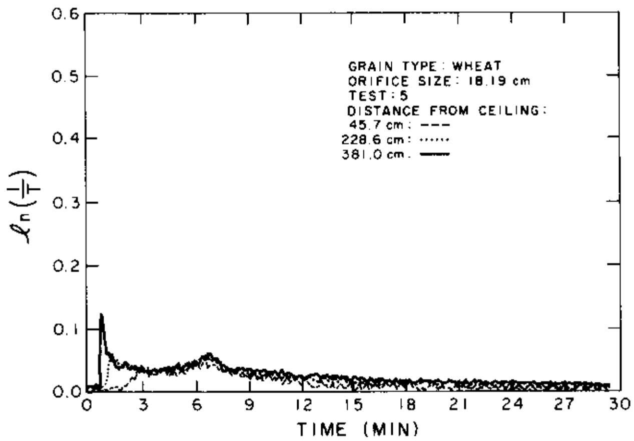

Fig. 4—Light attenuated by a dust cloud created by grain falling into a grain bin - Test 5.

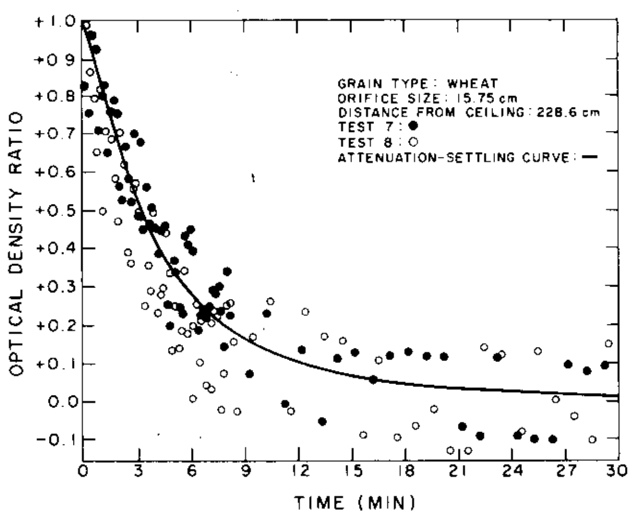

Fig. 5—Light attenuated by a settling dust cloud, experimentally measured and predicted by equation [10], Test 7-8, 228.6 cm from the bin ceiling.

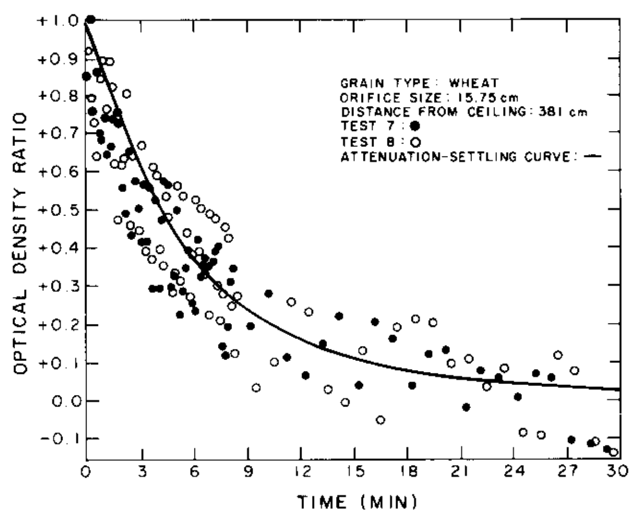

Fig. 6—Light attenuated by a settling dust cloud, experimentally measured and predicted by equation [10], Test 7-8, 381 cm from the bin ceiling.

shown. Table 3 contains a comparison between the predicted and experimentally measured particle size distribution in the grain bin in each test. Similar results for the dust concentration are given in Table 4.

The optical density as a function of time is shown at three positions for tests 1, 3, 4, and 5 in Fig. 1, 2, 3, and 4 respectively. After 3 min of grain flow the optical density was reasonable constant up to the time when grain flow was stopped.

The dust cloud is established rapidly in the botton of the bin for all of the tests. As the cloud rises in the bin the second light beam from the bottom detects the cloud, and then finally the third beam also detects the cloud. However for those tests in which the optical density was

TABLE 2. PARAMETERS USED IN EQUATION [10] THAT ARE PLOTTED IN FIGS. 3 TO 15

Test	a_1, μm/cm	b_1, μm	Standard deviation	$(\frac{b}{a})$, cm
1 and 2	0.0264	2.88	1.50	150
3	0.0106	6.48	1.50	350
4	0.00908	5.79	1.55	200
5 and 6	0.00502	4.31	1.80	150
7 and 8	0.00340	7.69	1.55	200

small at the botton of the bin, the optical density at the top of the bin did not even rise above noise in the measurement, as shown in Fig. 4. After the cloud is established, the optical density still may fluctuate about a reasonably constant value. In test 4, Fig. 3, the value changed by as much as 0.15 in less than 2 min. The maximum value in any of the tests was 0.57 which occurred in Fig. 4. The lowest maximum value was approximately 0.1. Such low dust levels occurred in all of the wheat tests.

After the grain flow stopped the optical density began to decrease as the dust cloud began to settle. The optical density measured at the top of the bin changed the most rapidly. The values measured at lower positions responded more slowly. The normalized optical density for each test at a specified distance from the ceiling of the bin is shown in Fig. 5 and 6 for 30 min after the grain flow stopped. Also shown in these figures is the light attenuation curve predicted by equation [10]. The parameters used in equation 10 for each test are listed in Table 2. The fit of this equation to the data is quite reasonable since only one set of parameters were selected for each test. The equation was assumed to correctly predict the effect of the distance from the bin ceiling. If we then assume that the fit of equation 10 to the data is adequate, then the parameter listed in Table 2 may be assumed to accurately characterized the dust cloud. The particle size of the dust at any position in the cloud can then be predicted by using equation 12 or the parameter a_1 and b_1 listed in Table 2. In Table 3 the particle sizes of dust in the clouds as predicted by the above procedure are listed. In addition, the particle sizes of dusts collected by settling plates and a high volume sampler are listed. The comparison between the size of the dust from the high volume sampler and that predicted by the attenuation settling method is very good in tests 3 or 4. The values differ by less than 1 μm. However, the comparison between the other was not as good. The size of the dust from the settling plate also was noticeably different from the size obtained from the dust collected by high volume filter. Size information could not be obtained from the settling plates in tests 5, 6, 7 and 8 because an insufficient quantity of dust was deposited.

The repeatability between those tests in which the same grain flow rates and type of grain were used is very good. A comparison between tests 1 and 2, tests 5 and 6, and tests 7 and 8 show only slight variation in all of the measured values in Table 3. A notable exception is the particle size obtained for the dust collected on the top settling plate in tests 1 and 2. The particle sizes of the dust collected in the high volume samples and the bottom plate in tests 1 and 2 agree within 0.2 μm. The

TABLE 3. COMPARISONS BETWEEN THE PARTICLE SIZE PREDICTED BY EQUATION [10] AND THE SIZE EXPERIMENTALLY MEASURED

Test	Attenuation settling			Experimental			Particle size difference
	Distance from ceiling, cm	$g_{g,3}$, μm	σ_g	$d_{g,3}$, μm	σ_g	Sample method	Attenuation settling - Experimental, μm
1	228.6	14.6	1.5	16.4	1.8	Plate	1.8
1	326	18.8	1.5	13.1	1.48	High vol.	+5.7
1	381	21.2	1.5	16.8	1.62	Plate	+4.4
2	228.6	14.6	1.5	14.9	1.54	Plate	-0.3
2	326	18.8	1.5	13.1	1.47	High vol.	+5.7
2	381	21.2	1.5	16.6	1.65	Plate	+4.6
3	45.7	11.4	1.5	16.7	1.54	Plate	-5.3
3	228.6	14.6	1.5	19.5	1.60	Plate	-5.1
3	326	16.2	1.5	15.7	1.58	High vol.	+0.5
3	381	17.2	1.5	18.5	1.75	Plate	-1.3
4	45.7	11.0	1.55	15.9	1.56	Plate	-4.9
4	228.6	14.0	1.55	16.7	1.55	Plate	-2.7
4	326	15.6	1.55	16.5	1.61	High vol.	-0.9
4	381	16.4	1.55	19.6	1.66	Plate	-3.2
5	228.6	15.4	1.8	--	--	--	--
5	326	16.7	1.8	11.9	1.56	High vol.	4.8
5	381	17.5	1.8	--	--	--	--
6	228.6	15.4	1.8	--	--	--	--
6	326	16.7	1.8	10.2	1.59	High vol.	+6.5
6	381	17.5	1.8	--	--	--	--
7	228.6	15.1	1.55	--	--	--	--
7	326	15.7	1.55	10.2	1.70	High vol.	+5.5
7	381	16.0	1.55	--	--	--	--
8	228.6	15.1	1.55	--	--	--	--
8	326	15.7	1.55	10.1	1.56	High vol.	+5.6
8	381	16.0	1.55	--	--	--	--

TABLE 4. COMPARISON BETWEEN THE DUST CONCENTRATION PREDICTED FROM THE RESULTS IN TABLE 3 AND EQUATION [10] COMPARED AGAINST THE DUST CONCENTRATION MEASURED WITH A HIGH VOLUME FILTER

Test	Distance from ceiling, cm	Attenuation-settling			Experimental
		$[\ln(\frac{1}{T})]_{Ave}$	$\left[\frac{2\rho_p d_{a,3}^3}{3LKd_{a,2}^2}\right]$, g/m³	Predicted concentration, g/m³	High volume concentration, g/m³
1	228.6	0.0608	6.72	0.409	— —
1	326	- -	- -		0.812
1	381	0.189	9.76	1.84	— —
2	228.6	0.0670	6.72	0.451	— —
2	326	— —	— —		0.904
2	381	0.166	9.76	1.62	— —
3	45.7	0.182	5.25	0.955	— —
3	228.6	0.254	6.72	1.71	— —
3	326	— —			2.35
3	381	0.286	7.92	2.26	
4	45.7	0.187	5.00	0.934	— —
4	228.6	0.262	6.36	1.67	— —
4	326	— —	— —	— —	2.77
4	381	0.322	7.45	2.40	— —
5	228.6	0.0293	6.48	0.190	— —
5	326	— —	— —	— —	0.126
5	381	0.0322	7.36	0.237	— —
6	228.6	0.0328	6.48	0.212	— —
6	326	— —	— —	— —	0.133
6	381	0.0475	7.36	0.350	— —
7	228.6	0.0100	6.86	0.0686	— —
7	326	— —	— —	— —	0.066
7	381	0.0441	7.27	0.320	— —
8	228.6	0.0134	6.86	0.0919	— —
8	326	— —	— —	— —	0.071
8	381	0.0175	7.27	0.127	— —

geometric mass median diameter of the dust collected from the top plate in test 1 is 1.5 μm larger then the size measured in test 2. We can give no explanation for this anomaly at this time.

The concentration of dust in the dust cloud was measured optically and by using a high volume filter. The filter was operated for 20 min after the start of grain flow. In order to be able to compare the data from the optical measurement of the dust concentration, an instantaneous measuremet, and the data from the high volume, an averaging method, the optical density measurements were averaged with respect to time from the time the grain flow started to the time the airflow through high volume filter was stopped. This averaged optical density for each test is given in Table 4.

The dust concentration predicted by the optical density, particle size (Table 3) and equation [13] were listed in Table 4, along with the concentration measured by the high volume filter. Since none of the measurements of optical density were at the same distance from the ceiling as high volume filter no direct comparison is possible. However, in those tests in which a somewhat vertically uniform cloud was present, i.e. tests 3 and 5, a good comparison exists. In test 3 the average concentration measured optically was 1.67 g/m³ and that obtained with the high volume sampler was 2.35 g/m³, and in test 4 values of 1.67 and 2.77 g/m³ were found respectively. In tests 1 and 2, a vertically nonuniform cloud was present, however, the predicted values of concentration optically measured above and below the high volume sampler bracketed the values measured with the sampler. In test 5, 6, 7 and 8 very low concentrations of dust were measured both optically and with the sampler. The value optically measured was approximately two to five times larger than those measured with the high volume sampler. This can be attributed in part to the fact that the particle size measured optically was approximately 50% larger than that obtained by the sample method. However, the most obvious reason for the large error is that the concentrations were low enough to be strongly affected by the error in the measurement.

CONCLUSIONS

1. The temporal variation of light attenuated by a settling dust cloud can be used with equation [10] to estimate the particle size distribution of the dust in the cloud.

2. The particle size and optical density can be used to estimate the dust concentration of the dust in the cloud.

3. Neither of the above measurements appears to be accurate when the dust concentration is less than 0.5 g/m³. The concentration of dust generated by wheat falling into a grain bin was so low that only an order of magnitude estimate of both the particle size distribution and concentration can be made optically.

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