Methods of Estimating the Dustiness of Industrial Powders – A Review[†]

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Abstract

The industrial handling procedures for bulk materials, for example, to store, to convey, to mix, and to fill, etc. often lead to dust emissions. The generated dust is closely related to health hazards and environmental pollution, and is also a cause of fires and explosions. The particle size distribution and concentration determine the risks. The dust liberation property of disperse particle systems – so-called powders – depends on a multitude of variables and also on the method and intensity of stressing. The present paper describes practically all the dust measuring methods published in literature. It also presents related particle sizing and counting techniques and systematically summarises the integrated measurement methods.

1. Introduction

The handling of materials, i.e. storing, conveying, filling, and mixing leads to dust liberation. This capability of generating dust is described as dustiness. Changing unit operations, including micro-encapsulations, masterbatches, and lost packages, have led to a reduced dustiness index of disperse goods [1, 2]. Because of necessary simplifications of the material stressing characteristics, the standardization of measurement methods did not prove suitable [3].

Two standardized methods for determining a dustiness index for pigments and fillers are described in DIN 55 992: the rotating drum apparatus and the single-drop dustiness apparatus [4]. To meet the requirements of occupational health, hygiene and safety, as well as those of fire and explosion prevention, the estimation of dustiness is becoming more and more important. Dustiness prevention by means of dustiness estimation even before a new method is installed or material is changed is the objective of process engineers et al. [5, 6]. One model for estimating the correlation between separation forces, binding forces and dustiness has been developed by Plinke [7]. Efforts are being made to develop standards for reproducible methods to achieve the dustiness index for bulk mate-

rials in context with occupational safety [8].

Excessively simple measurement methods fail because of two crucial reasons: On one hand, dustiness depends on the kind of stressing, i.e. the dustiness index during transfer can be below the index during mechanical stressing. And on the other hand, the special characteristics of the materials, for example the humidity, density, and morphology, differ over a wide range, turning the topic “dustiness” into an interdisciplinary subject including quality management for products, occupational safety, environmental protection, and fire and explosion prevention.

Consequently, one sole method will not be able to extensively simulate all important influences on dustiness capability. Many studies have proved the influence of inert powdery material on the human organism [9, 10]. Contact with these materials can lead to industrial diseases. According to Wichmann, particles $< 1 \mu\text{m}$ have a particular effect on human health. Known occupational diseases are, for example, Byssinosis caused by cotton in the seed, the baker's flour aversion, and metallic pneumoconiosis caused by the handling of metal (hard alloy or aluminum pneumoconiosis) [10-12].

The first studies on nano-sized particles and their increased importance showed significant effects on affected groups of persons based on correlations between emitted nano-sized particles during modern combustion processes and an increased number of allergy symptoms [10]. The studies also made evident

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that nano-sized particles are emitted during most treatment processes [13].

Occupational safety as an example shows that the evaluation of the dustiness potential during the handling of disperse materials is of significant importance. If new materials are to be used, the expected dustiness will be an important judgment criterion.

2. Aims and requirements

The currently increased interest in dustiness estimation is based on the involved fields of occupational safety, health, hygiene, and fire and explosion prevention. The reduction of the airborne dust load as early as the planning phase of manufacturing processes through improved estimation models is the principal goal [5, 6]. This enables the reduction of secondary measures such as extraction systems, provided the technical requirements of the products are no obstacle.

Due to the integration nature of the total dust method, conclusions about particle size distribution are impossible. More appropriate methods will permit conclusions about particle size distribution. Corresponding requirements are, for example, standardized in DIN EN 481 [14], which classifies inhaled particles into 3 categories.

The penetration depth depends on the particles' aerodynamic diameter. **Fig. 1** displays the classifica-

tion of aerosols in the respiratory system, according to occupational health criteria.

The characteristics of materials, especially the physical ones, are often of increased interest. They are related to the dwell time of the particles in the air and their correlated particle mobility. Increasing particle mobility leads to a higher contamination risk.

The correlation between material stressing and the amount of emitted dust must be retraced by the measurement methods. Basically, the acceptance of the methods is increased through simple handling and high reliability. Additionally important for the economic aspects are versatility in use, easy handling, fast and reliable results, and easy cleaning. High efficiency leads to lower costs [16].

3. Historical methods of dustiness measurement

In the face of the variety of methods used for measuring the dustiness capacity of materials, the choice of appropriate apparatus is difficult.

Basic factors of choice are comparability to field conditions and the kind of output data (loaded filter or displayed results).

The comparability of results of different methods is often difficult because of the different time and kind of stressing, as well as the means of evaluation and sampling. By using modern particle measurement techniques, conclusions about the particle size fraction are possible.

Early studies were made in 1922. Andreassen et al. [17], for example, investigated the dustiness of 24 sample substances by using a single-drop apparatus (**Fig. 2**). Additionally, they described the influence of small particles on particle collectives and their capability of generating dust. Andreassen used a device consisting of a modular-design dust chamber and two fitted and sealed falling tubes. An iris is used as the shutter. The sample is placed on the iris and covered by a flat-turned tray to seal the sample against the influence of ambient air. Six metal slides are inserted successively from bottom to top into the dust chamber after the sample has been dropped.

The time interval of insertion is defined by a metronome. After the test, the slides are weighed. The height of the falling tube has not been documented.

ANSI/ATSM D547-41 standardized a modified method to investigate the index of dustiness of coal and coke. The initial method has been known since 1939 [18]. This method also uses the single-drop dustiness technique (**Fig. 3**). The dust chamber is

Fig. 1 Classification of airborne aerosols according to occupational health criteria [15].

Fig. 2 Single-drop dustiness apparatus used by Andreason. [17]
a. cover, b. iris, c. slides, d. modular casing, e. falling tube part 1, f. falling tube part 2

Fig. 3 ANSI/ATSM D547-41 [18] standardized device to investigate the dustiness index of coal and coke, a. cover, b. upper slide (sample to be tested), c. stop watch, d. guides, e. slide for coarse dust, e. slide for float dust, f. drawer

sealed after the sample (22.7 kg) has been placed on the inserted upper slide. After drawing out the upper slide abruptly, the sample drops into the bottom drawer. Exactly 5 s later, both lower slides are inserted quickly. The top slide is pulled out after two minutes, the lower slide after 10 minutes. By weighing the two slides, a dust index is generated for coarse and float dust.

4. Characterization of airborne dust

4.1. Filter samplers

Filter samplers consisting of filter housing and filter are used as a standard measurement method. The whole airborne dust is collected in the filter, whereas conclusions about the particle size distribution are only possible by means of further measurement.

Fractional sampling units are used for the fields of occupational health and safety to deposit inhalable and respirable dust fractions [19]. With the aid of these techniques, non-conformity during further measurement can be avoided.

4.2. Foams

Metal and polymer foams with defined pore sizes are used alternatively [20]. The results are in accordance with the demands of DIN EN 481 (**Fig. 4**).

Fig. 4 Classification of inhalable aerosols into health-related fractions according to DIN EN 481

4.3. Impactors

Impactors are often used to fractionally measure the dustiness. They can easily replace filter samplers in the test apparatus. Impactors can measure only low particle concentrations. Therefore the dust-laden air has to be diluted. The air velocity at the inlet has to be adequate to prevent particle sedimentation. Other-

wise, the particle size distribution alters. This problem is solved by isokinetic sampling combined with dilution. The disadvantage of this method is difficult handling, and time-consuming measurement and cleaning [20].

4.4. Elutriators

These are rarely used units. Particle-laden air flows between several parallel plates. The distance between the plates and the air velocity define the deposited particle fraction [20].

4.5. Optical measurement methods

These methods are commonly used in single-drop dustiness units. The dust concentration in the chamber is assessed by reducing the intensity of a laser beam. Additionally, some devices are able to analyse particle size distribution [16, 21].

Alternatively, counted particles can be assigned to equivalent defined particle sizes by analysing scattered light signals. This method is only able to handle low particle concentrations, causing inaccurate results and more difficult handling.

Easy handling, short cleaning periods and, in particular, the ability to draw mass-correlated conclusions, are the advantages of this method.

4.6. Further methods

Due to the increasing importance of nano-sized particles, further studies in this field are absolutely necessary, thus requiring special techniques. During earlier studies, TEOM systems proved reliable. The implementation of otherwise approved methods such as SMPS or APS systems needs to be studied extensively (acronyms are explained in chapter 8).

5. Apparatus for measuring dustiness of disperse powders

5.1. Single-drop dustiness apparatus

Usually, single-drop dustiness apparatus consists of a dust chamber and a falling tube sealed off with a shutter, as shown in **Fig. 5**. The sample is poured into the funnel above the falling tube. By opening the shutter briefly, the sample falls through the falling tube into the dust chamber and drops onto the bottom, thus generating dust. The dust concentration is assessed by the reduction of intensity of a laser beam. The reduction opacity is transformed into the dust index [22-43].

This concept using a dust chamber is not the only one: The method according to DIN 55992 [4] as-

Fig. 5 DIN 55992-2 [4] standardized single-drop dustiness apparatus to generate a dustiness index of fillers and pigments, a. funnel, b. shutter, c. falling tube, d. laser and detector, e. suction connector, f. base plate with ejector

sesses the dust index inside the falling tube itself. Another device marketed commercially in England draws the generated dust onto a filter [23]. In this case, the shutter is open to prevent low atmospheric pressure in the dust chamber. Single-drop dustiness units are laboratory devices which bring fast and reliable results. The measured dustiness index is usually below those assessed by other methods [23].

Due to low mechanical stressing of the sample, it can be assumed that the sample does not alter [20]. On the assumption that the particle movement during sedimentation has reached a steady state, a statement about the particle size distribution is possible.

The height of drop varies between 0.5 m and 1 m, some special devices going up to 3 m [24]. The sample mass varies between 5 g and 3 kg, usually between 30 g and 100 g. In most cases, the sample is dropped suddenly in one load, whereas in some special devices it is a continuous process, for example, by means of a conveyor belt.

For a single-drop dustiness apparatus, the variation of the results during one sample row is higher than with other methods [23].

During gravimetric measurement the amount of total dust is one possible result. Adjusted techniques allow conclusions to be made about certain fractions.

Optical measurement techniques enable the determination of the dustiness index function, allowing the reduction of airborne dust to be plotted over time in a graph and thus conclusions to be drawn about the particle size. The arrangement of measurement units has a considerable influence on the results. Higher values are to be expected if the light shines through the falling stream. By positioning the light beam to the side of the falling stream, only the generated dust is counted [26].

This measurement device has the advantage of easy handling, simple construction and fast measurement. Easy and fast cleaning, short time preparation for further tests, and self-clean fittings [16] are also an advantage.

5.2. Rotating drum apparatus

The stressing of the sample in the air-flow drum is similar to that of various rotating drum methods [44-63]. Dust generated from the sample is transferred to a measurement unit and collected by a filter or directly analysed. Lifter bars inside the drum prevent the sample from getting stuck on the drum. Filters, impactors and optical particle counters are used as measurement units. It must be taken into account that the air flow velocity is a determining factor for the particle size distribution and particle concentration. **Fig. 6** shows a typical test apparatus.

Related to the pressure ratio in the drum, two techniques can be distinguished, one with overpressure and the other below atmospheric pressure.

Fig. 6 The Warren Spring Laboratory, U.K. [23] rotating drum tester, a. outlet, b. sampling unit, c. rotameter and air-flow controller, d. gauge, e. pump, f. drive motor, g. driven roller, h. inlet, i. drum

5.3. Inverse-flow drop apparatus

By charging the sample over a longer period of time, this method simulates continuous transfer [64, 74]. Sample transfer is possible via conveyor belt [64] or conveyor worm [65].

The MRI Tester [45] charges the sample by means of a tiltable beaker (**Fig. 7**). The filled beaker is tilted continuously, the sample drops from a height of 25 cm onto the aluminum-foil-covered foam pad of the dust chamber. The generated dust is transported by an air stream that enters the tester through two side baffles and exits it to the top. During this process, larger particles are sifted out due to their higher settling velocity. Depending on the aim of research, a filter or an impactor is used. The use of optical measurement units is not known in scientific literature. The smallest possible settling particle is defined by the air velocity.

Fig. 7 “MRI-Tester” developed by C. Cowherd [69], a. filter, b. vibrator, c. beaker, d. aluminum foil, e. foam pad, f. beaker rotating mechanism, g. impactor

5.4. Gas fluidization dustiness tester

The fourth class of method for testing dustiness, as schematically shown in **Fig. 8**, applies a gas fluidization dustiness tester [75, 77]. This device often consists of a vertical stainless steel cylinder and glass modules. The sample is placed onto the sintered plate

at the lower end of the tester, where it is continuously subjected to an upward air stream. Cohesive material needs an agent in order to perform homogeneous fluidization. Sand was chosen as the agent to perform a homogeneous fluidization [76].

Particles with a low settling velocity are carried to the upper outlet by an air stream. They are collected by a filter [3], measured by an optical particle counter, or analysed by a TEOM. Due to the high energy input, agglomerates or pellets are destroyed.

Therefore, gas fluidization dustiness testers are the most stressing class of method for dustiness tests. Due to collisions, inter-particle bonds between test materials are destroyed. This intensive stressing of the sample permits conclusions to be made about the ability of generating dust for only a limited range of application.

Additionally, the dustiness of a material depends on material properties such as the density of material, the form, and the particle size distribution [3, 78]. The dust index increases as the median diameter decreases, as stated in the Sethi investigation [75, 76], contradicting the model of Plinke [7].

Fig. 8 Gas fluidization tester designed by Sethi and Schneider [75,76], generated data of PM 1, PM 2.5, PM 10 by TEOM, a. optical particle counter, b. glass module, c. pressure measurement taps, d. TEOM, e. cyclone, f. diluter

5.5. Resuspension chamber

Visser [79, 80] studied the influence of air velocity and air humidity on coal by means of a resuspension chamber. The experimental set-up consisted of a conveyor belt, a rectangular wind tunnel and filter samplers (**Fig. 9**). The conveyor belt is positioned horizontally at 90 degrees to the main air stream.

The coal layer (0.08 m) is continuously supplied by the conveyor belt and dropped through the air stream into a container underneath the wind tunnel. The grille separating the container from the wind tunnel prevents the re-entry of dumped coal. A thin coal stream is dispersed by the air stream in the wind tunnel, the dust concentrations being measured downstream.

Nine equidistant squarely positioned samplers are installed downstream. While horizontal in-line samplers showed approximately equal dust concentration, vertical in-line samplers detected different concentrations. To permit visual evaluation, the tunnel consists of glass modules.

Fig. 9 Visser used a resuspension chamber [79], a. wind funnel, b. covered conveyor belt, c. pitot tube, d. grille, e. dustiness chamber, f. sampler

5.6. Special designs

The methods of this group cannot be assigned definitively to any one of the preceding groups. Some of them are genuine special designs, others are combinations of preceding methods [81-84].

With the aid of two examples, these methods are described in greater detail. The method developed by the "Getreideforschungsinstitut Potsdam" characterizes the dustiness of flour and bread improvers. Especially in the baker's trade, these dusts are responsible for most occupational diseases.

The device used is placed on a base plate (2.5 m × 1 m), which is surrounded by 3 glass wall elements (height: 0.6 m). The device is not covered.

The gas-particle mixture is generated by a dust disperser. The dust disperser is positioned at the open

end of the device. The gas-particle mixture is injected at a height of 400 mm above the base plate. At a distance of 1.3 m from the dust disperser, samplers for respirable and inhalable fractions are installed which collect dust simultaneously, as shown in **Fig. 10** [82].

Fig. 10 The dustiness tunnel [82] suggested in DIN 33897-3 a. sampler for inhalable dust fraction, b. sampler for respirable dust fraction, c. compressor, d. disperser, e. dust tunnel

In the course of a European research project, a combination of a single-drop dustiness apparatus and a rotating drum was developed [20]. This device consists of a two-part drum connected to the opposite sides of the chamber of a single-drop device (**Fig. 11**).

Due to the modular system, the device can be used

Fig. 11 Combined HSL single-drop tester on the HSE/WSL MK2 rotating drum apparatus [20], a. falling tube with fitted funnel, b. outlet, c. sampling point, d. inlet, e. divided drum

as a single-drop tester, a rotating drum tester and as a combination of both. Both devices are proven designs. The inlet and outlet cones of the HSE/WSL MK2 [3] are modified in order to assure laminar flow.

The cone-shaped outlet causes the dust-laden air to accelerate up to 4 cm/s. At the outlet, a measurement unit is installed. The measurement unit consist of two porous polyurethane foams and one filter.

This unit leads to sampling according to DIN EN 481 [14]. The drop unit was developed to be similar to the Roaches dustiness drop tester [25]. This combination allows simulations of varying kinds of stressing, for example conveying or filling. Polyurethane foams are sensitive to moisture. Therefore, monitoring of the humidity is necessary [20].

6. Dustiness measurement systematics

The multitude of introduced methods and the possibility of combining them demonstrate the complexity involved in selecting an appropriate method for dustiness measurement.

Many manufacturers of powders and bulk materials as well as institutes use their own measurement methods. The results of those methods are not comparable or cannot be compared easily. Various fields of application do not allow a uniform apparatus.

For the future development of materials with reduced dustiness behavior, improved methods of simulation will be necessary, whereby the interaction of particulate matter and dustiness estimation needs to be investigated to counter dust generation. **Figure 12** displays a systematics about the methods used and their combinations.

In principle, a dustiness measurement of powders is subdivided into four areas: sample application, sample stressing, sampling, and analysis.

In the first three areas, the procedure can be discontinuous (e.g. single drop), continuous (e.g. continuous drop), and intermittent (e.g. periodic drop).

The selection depends on the kind of powder stressing, the amount of liberated dust and the dust fraction of interest.

To systematize all the methods needs more than a plain list. These methods can be summarized, e.g. by the kind of stressing, as done in this article, but it will not be of general use. This special kind of gradation does not permit reliable conclusions about the measurement units used such as impactors, filters, or TEOM [19, 55, 78, 85-101]. A useful systematic scheme of all methods (including all combinations and permutations) is still under construction.

Fig. 12 Systematics to classify apparatus for the determination of the dustiness of powders.

7. Conclusions

The present discussion on adequate measures to permit meeting the dust limits for workplaces was initiated by the realization of the harmful effects of dust as well as by the legal definitions for inhalable and respirable particles.

Initial monitoring of the building industry made it evident that about 40% of the samples taken were far above legal limits [15].

Although meeting the legal limits is sometimes hardly possible, further reduction of the limits is necessary in order to meet the requirements of occupational health. This causes a contradiction in terms. This conflict proves the importance of preventative measures against dust generation. The estimation of dustiness is directly correlated to these preventative measures.

Current methods permit the amount of liberated dust to be estimated. But it is impossible to prove direct correlations between the dustiness indices assessed during different kinds of stressing. The comparability of results of different methods is hardly possible. As a conclusion, it does not seem sensible to aim at one standardized method.

The future development of low-dustiness materials demands research on other characteristics. While the influence of the moisture content on dust generation has been scrutinized, other properties such as particle density and shape have not been considered sufficiently.

These stated problems will serve as a basis for future research.

8. Explanations

Masterbatch	For example, a coloring agent concentrate is called a masterbatch in granular, paste or liquid form to ink a natural-colored granulate.
Lost packages	A hazardous material added to the application by closed packing [102].
Inhalable dust	Inhalable dust fraction according to DIN EN 481 [102]
Respirable dust	Respirable dust fraction according to DIN EN 481 [102]
SMPS	A <u>Scanning Mobility Particle Sizer</u> measures particles with a mobility diameter from 3 to 1000 nm.
TEOM	A <u>Tapered Element Oscillating Microbalance</u> measures particle concentrations according to PM-10, PM-2.5, PM-1 and TSP in real time.
APS	An <u>Aerodynamic Particle Sizer</u> is used to study particles with an aerodynamic diameter from 0.37 to 20 μm in real time.
TSP PM	<u>Total Suspended Particulate Matter</u> <u>Particulate Matter</u>

9. Literature

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Eberhard Schmidt is full professor and head of the Division of Safety Engineering/Environmental Protection at the University of Wuppertal. He earned his scientific degrees at the University of Karlsruhe as a member of the Institute for Mechanical Process Engineering and Mechanics. As a visiting scientist at the Institute for Safety Technology at the Joint Research Centre in Ispra/Italy he gained international experience and as R&D engineer in Degussa's Department of Process Technology and Engineering in Wolfgang/Hanau he became acquainted with industrial processes. Current research in Wuppertal deals with gas-solid particle separation (emission control or product recovery), dust generation caused by powder handling, modelling and simulation of particulate systems, and water recovery by membrane processes.

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