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Ignition Temperatures of Dust Layers: Flaming and Non-flaming

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Combustible dusts, based on tests conducted in the Setchkin Furnace on five representative dusts, are shown to have two distinct layer minimum ignition temperatures, designated MIT_{son-faming} and MIT_{daming}. The MIT_{son-faming} is the one usually reported in the literature; the MIT_{faming} is determined by starting at a much higher temperature and working downwards. MIT_{faming} can yield a different ranking of dust flammability than MIT_{son-faming}. The MIT_{faming} appears to be more closely correlated to the MIT of dust clouds and to the test prescribed for flammable solids in the US Code of Federal Regulations than the MIT_{son-faming}.

INTRODUCTION

The measurement of minimum ignition temperatures (MIT) of dust layers has been carried out routinely for many years.¹ The purpose has been to determine the maximum temperature of surfaces on which the dust can accumulate without the possibility of fire. This information can be used, for example, to specify the maximum temperature allowed for electrical boxes or for a hazard study of a factory.

There are two general methods of measuring the MIT of dust layers. One is to use a hot-plate, in which case only the bottom of the sample is exposed to the high temperature. The other is to use a furnace, usually tubular, in which case the sample is heated on all sides more or less uniformly. Both methods have their advantages: the hotplate is representative of more industrial situations; the furnace yields a lower (i.e. more conservative) value.

Recently, Miron and Lazzara² have described MIT tests carried out on several dusts using a hot-plate method. Only one dust yielded flaming combustion. The MIT of cornstarch could not be measured because of swelling of the dust.

The present study reports measurements of the MIT using the Setchkin Furnace. This apparatus was designed to measure the MIT of plastics;³ it has been previously used for dusts, and the results were similar to those of the Godbert-Greenwald furnace generally employed for the measurement of the MIT of dust layers.⁴

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

The Setchkin furnace is described fully in the ASTM Standard.³ The complete apparatus, except for the sample holder, a mirror and thermocouples, was purchased from Custom Scientific Instruments and included a control module with a data logger for the thermocouples. The sample holder used for the dust was a porcelain crucible, 32 mm diameter by 20 mm high (Coors model 60133), placed in a stainless steel ring welded to a stainless steel rod, which could be hooked onto the sample rod of the furnace. A mirror was installed

tormaximum hazard which was then put into the furnace. The furnace was heated until combustion was observed. Most of the tests were carried out under the 'constant temperature' mode. The furnace was heated to the desired temperature and the crucible with the sample was then quickly placed in the furnace. In the case of tests for

quickly placed in the furnace. In the case of tests for flaming combustion the sample would either burst into flames within a few minutes or would combust without flaming. Further tests were carried out until the boundary between non-flaming and flaming combustion was determined to within 10°C.

to allow observation of the sample during the test. A

3 mm diameter Type K thermocouple was used to monitor the temperature below the furnace; another was

In order to obtain an idea of the appropriate starting

point, a few tests were carried out in the 'rising temper-

ature' mode. The dust sample was placed in the crucible

employed to monitor the temperature in the sample.

In the case of tests for non-flaming combustion the temperature-time graph was used as the criterion. The existence of an exotherm could be detected by the observation of an inflection point on this graph. This point occurred between 10 and 30 min after the crucible was placed in the furnace. When no inflection was observed, the maximum temperature of the thermocouple in the sample was only a few degrees, at most, above the furnace temperature. (It is necessary to run the test until the maximum temperature has been reached in order to ensure that a false negative has not been obtained.)

When an inflection was observed, the maximum temperature rise was substantial. It depended on the size of the sample—e.g. for 2 g of Pittsburgh standard coal dust (which resulted in a layer thickness of 12 mm) the temperature rise was at least 50°C. The boundary between combustion and non-combustion was sharp and was determined within 10°C.

Based on measurements of the temperature distribution in the furnace and taking into account other errors, such as the effect of inserting a cold crucible into the hot furnace,^a the estimated accuracy of the MIT determination by this method is $\pm 10^{\circ}$ C.

Five dusts, namely lycopodium, Pittsburgh standard coal dust, cornstarch, Quintette coal dust and potato starch, were tested. The first three are widely used as reference dusts in dust explosion studies and the other two were of interest for the reasons discussed below. Lycopodium, a naturally occurring spore which has a consistent particle size of about 30 μ m, was obtained from EM Industries, Pittsburgh standard coal dust was supplied by the US Bureau of Mines, Quintette coal dust by the mine and the two starches by the respective manufacturers.

EXPERIMENTAL RESULTS

The effect of flow rate of air on the apparent MIT of Pittsburgh coal dust was measured in the range of $0-6 \text{ cm s}^{-1}$ using a sample size of 2 g. The variation was less than 5°C, which is within the accuracy of the test. It was anticipated that this factor would not be important, otherwise the meaningfulness of the data would have been in doubt. Most of the following tests were carried out at a flow rate of about 5 cm s⁻¹.

The MIT_{non-flaming} of Pittsburgh coal dust is shown as a function of sample mass in Fig. 1. For a mass of 0.1 g, there was no indication of reaction up to 380°C. Thus, there appears to be a minimum sample size below which there is no reaction. It would appear that the curve reaches an asymptotic value of about 170°C for large masses. For a layer thickness of about 12 mm, the value obtained here of 190 \pm 10°C is higher than those obtained in the Godbert-Greenwald furnace of 170°C⁵ and 175°C.² The reason may be due to the different shape of sample holder used in the Godbert-Greenwald furnace. A 12 mm thick layer in the latter corresponds to a sample mass of 8 g, which from Fig. 1 should yield an MIT of about 180°C, in reasonable agreement with the literature data.

The MIT_{non-flaming} of lycopodium is also shown in Fig. 1. Unlike Pittsburgh coal dust, lycopodium did combust when a very small sample mass (0.1 g) was used. The asymptotic value (about 185° C) is reached at a smaller mass than for Pittsburgh coal dust. The literature value usually quoted⁶ is 310° C, although recently, Miron and Lazzara² obtained 190°C in the Godbert-Greenwald furnace, in good agreement with our value.

A coal dust from the Quintette mine, located in Tumbler Ridge, BC, was of interest because of its very high minimum ignition energy (1000 J) obtained in explosion tests. The MIT_{non-flaming} obtained was 260° C for a 1 g sample and 250° C for a 2 g sample, which corresponded to layer thicknesses of 11 and 19 mm, respectively. The inflection points were difficult to detect, and the temperature rises were much less than those measured for Pittsburgh coal dust. The higher MIT_{non-flaming} for Quintette coal dust compared to Pittsburgh coal dust indicates that some correlation exists with minimum ignition energy, but the difference between the two is much less than would be expected from the difference in this energy.

The MIT_{non-flaming} of both the cornstarch and potato starch dusts were measured as $260 \pm 10^{\circ}$ C for 1 g samples. The literature data for cornstarch⁶ are in the range $330-410^{\circ}$ C although some authors^{2,4} report that measurements could not be made because the starch expanded during the test and the thermocouple did not remain in contact with the sample.

The MIT_{flaming} of Pittsburgh coal dust and lycopodium dust are shown as a function of sample mass in Fig. 2. The general shapes of the curves are similar to those of Fig. 1, except that the curves flatten out at a smaller mass. For a mass of 0.1 g of Pittsburgh coal dust, no flames were observed, only glow, at the maximum temperature attempted of 730°C. The MIT appears to reach an asymptotic value of about 550°C for Pittsburgh coal dust and 440°C for lycopodium.

The MIT_{flaming} of Quintette coal dust was measured to be 600°C for a sample mass of 1 g. The MIT_{flaming} for corn- and potato starches were, respectively, 540°C and 530°C. Tests carried out in the 'rising temperature' mode on all the dusts tested produced smoke and complete combustion of the samples, but without any flames.

DISCUSSION

Palmer⁷ has pointed out that both the hot-plate and the furnace methods are appropriate for determining the



Figure 1. Minimum ignition temperature (non-flaming) as a function of sample mass.



Figure 2. Minimum ignition temperature (flaming) as a function of sample mass.

MIT, depending on the industrial situation it is desired to simulate. On the other hand, Miron and Lazzara² state that the hot-plate test is closer to reality. They have presented evidence which shows that this produces higher MITs than the furnace method. On the other hand, Nagy and Verakis⁴ presented evidence that both methods yield similar MITs. From a heat-transfer viewpoint, the former seems more reasonable. The advantage of the furnace method is that it provides the most conservative values of the MIT, which should be applicable in all situations.

The MIT is well known to be a function of layer thickness. However, the limited evidence obtained in the present study suggests that sample mass is a more appropriate variable to use for the furnace tests than layer thickness, in contrast to the hot-plate method. In the case of the hot-plate, the heat is mostly absorbed by the bottom of the sample and lost from the top surface, assuming that the surface areas of the sides are small relative to those of the top and bottom. On the other hand, in the furnace method, heat is being absorbed from all surfaces and any heat generated by combustion is also lost from all surfaces.

The order of the ranking of different dusts by their MIT can give different results, depending on the sample mass. From Fig. 1 it can be seen that lycopodium has a significantly lower MIT than Pittsburgh coal dust at small masses, is about the same at 2 g, and perhaps may be higher at large masses.

The use of different types of furnaces (e.g. the Setchkin used in this study versus the Godbert-Greenwald, used more frequently) probably does not cause significant disagreements. The advantage of the Setchkin is that the continuous air flow through the vessel tends to make the temperature more uniform. Of more importance can be a difference in sample containers, as discussed above. It would probably be better if standard MIT values referred to thicker layers than the usual 5 or 12 mm thick layers because the slope of the MIT versus thickness decreases close to zero when the thickness is above 25 mm or, alternatively, the sample mass is greater than 1 g.

Although the starch samples swelled considerably when heated, there was no problem in observing an inflection point in the temperature-time graph, in contrast to other studies. The reason perhaps was the use in the present study of a relatively thick, rigid thermocouple; the sample swelled around it. Thinner thermocouples are more easily pushed out of the sample; bare thermocouples did not last long in the highly corrosive atmosphere. The starch samples showed clear evidence of combustion, i.e. char and smoke, in addition to the inflection point. Therefore it seems most reasonable and desirable to be able to define an MIT.

The concept of a second MIT for dusts, one that refers to flaming combustion, has apparently not appeared in the literature prior to this study. The $MIT_{flaming}s$ are much higher than the $MIT_{non-flaming}s$. However, they provide additional useful information on the hazards. For example, the $MIT_{non-flaming}$ of lycopodium and Pittsburgh coal dust are roughly the same. On the other hand, the $MIT_{flaming}$ of lycopodium is much lower than that of Pittsburgh coal dust (see Fig. 2). The difference is probably related to the nature and quantity of combustible gases released.

The US Code of Federal Regulations⁸ provides a test method for determining if a powder is a flammable solid, and consists of packing the dust into a metal boat and lighting it with a paraffin candle. (The specification does not stipulate the degree of compaction; tests were carried out using loose-poured and firmly tamped dust; no significant difference was observed.) Pittsburgh coal dust did not ignite at all in this test. Cornstarch turned brown and emitted a small amount of smoke, but did not produce a flame. Lycopodium did ignite. These results are consistent with the MIT_{flaming} but not with the MIT_{non-flaming}. It should also be noted that the Code of Federal Regulations test is quite a weak one.

The 'rising temperature' mode could not produce any approximate value for the $MIT_{flaming}$ presumably because the temperature rise was slow enough for the emitted volatiles to be diffused away before the temperature was sufficiently high to ignite them. This indicates that the $MIT_{flaming}$ is useful only in industrial situations in which room-temperature dust is exposed fairly rapidly to a high temperature.

The values of MIT_{flaming} (1-g sample size) are fairly close to the dust cloud MIT values measured by the Godbert-Greenwald method in this laboratory (Pittsburgh coal dust: 560°C versus 610°C, Quintette coal dust: 600°C versus 620°C, lycopodium: 450°C versus 470°C, corn starch: 540°C versus 470°C). Perhaps this should not be too surprising, since both processes involve fairly rapid devolatilization and subsequent ignition.

The novelty of the present work is the demonstration that two distinct MIT values can be determined on many dusts, depending on the starting temperature. Henderson and Tyler⁹ have reported a dual-ignition temperature for dust layers of sodium dithionite, which is attributed to a two-stage decomposition of the material. This is a different and less general phenomenon from the one described here, which has different modes of decomposition, i.e. flaming and non-flaming. These concepts were applied to a 'fire' (white smoke observed) that occurred around a prefilter inside a duct in a factory that used potato starch. Black residue was only found close to the prefilter. If flaming combustion had occurred, then soot would have spread a considerable distance. Thus, the temperature of the filter must have been sufficiently high to exceed MIT_{non-flaming}, but not high enough to reach MIT_{flaming}. It would be of interest to analyze the major gases evolved during combustion of dusts at different temperatures in order to understand the mechanisms involved.

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NOTES

Starting at 350°C, the temperature of the furnace drops about 10°C when the cold crucible is placed inside. The temperature recovers over 10 min. The temperature of the dust is (typically) about 30°C below the furnace temperature 1 min after insertion, about 13°C below 5 min after, and about 3°C below 10 min after.

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