A DUST EXPLOSION APPARATUS SUITABLE FOR USE IN LECTURE DEMONSTRATIONS

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Classroom demonstrations enhance the sensing learning style that many engineering students use. This simple apparatus, which can be constructed with components found at a local discount store for under $20, effectively demonstrates the nature of dust explosions. The demonstration can be used to complement a lecture in thermodynamics (combustion, heating, and rapid expansion of gases), process design (hazards involved with solids handling), or process safety (dust explosions and vent sizing).

Any combustible solid that can be reduced to a fine powder has the potential for involvement in a dust explosion. The Oxford Dictionary[1] defines dust as

> *Earth or other solid matter in a minute or fine state of subdivision so that the particles are small and light enough to be easily raised and carried in the wind; any substance comminuted or pulverized; powder.*

Typically, these solids are 1 to 50 microns in particle size. For an excellent overview about dusts and their hazards, the World Health Organization has an html document available on the web.[2]

Many accidental dust explosions occur during manufacturing operations associated with the preparation or use of such materials as pharmaceutical powders, wheat flour, wood processing, metallic powders, powdered coal, powdered sugar, powdered confectionery ingredients, etc. Eckhoff[3] reports that during the past twenty years, dust explosions have accounted for several hundred deaths and hundreds of millions of dollars in property damage. A recent dust explosion in Kinston, North Carolina, demonstrates how damaging these explosions can be (six people were killed and dozens were injured).[4] It is critical that controls be in place to prevent these events from happening.

Some additional teaching aids on dust explosions are available through SACHE products (CCPS-AIChE). Two products particularly suited to this experiment are the "Dust Explosion Control"[5] video/slide/lecture and the "Explosion"[6] video. The "power" of a dust explosion is quantized by a value called the deflagration index, K_{St}[7]

$$K_{St} = \left(\frac{dP}{dt}\right)_{max} V^{1/3} \qquad (1)$$

This value can be used to predict the over-pressure rate at a boundary using a scaled distance (volume to the 1/3rd power in the above equation). Aluminum powder, for example, has one of the highest K_{St} at 415 bar m/s. For comparison, the material used in the experiment described in this paper has a K_{St} of 151 bar m/s[8]. The textbook by Crowl and Louvar[9] provides more details related to mechanism and predictions involved with dust explosions. A source for minimum flammability concentrations for many types of dusts (including agricultural products, carbonaceous dusts, chemical dusts, metal dusts, and plastics) can be found in Appendix D of the

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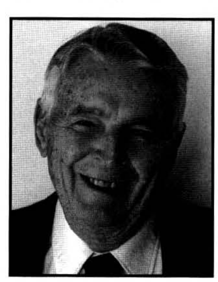

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NFPA 68 Guide for Venting of Deflagrations.[10]

EXPERIMENT DESCRIPTION

A transparent plastic food storage box with a snap-on lid, about 15 centimeters square and 18 centimeters in height, available at department and general merchandise stores (hereinafter called "the box"), provides a satisfactory container for the demonstration. The exact size of the box is not important, but its side walls should be transparent. An aluminum foil heat shield should be attached to the inside surface of the snap-on lid—sticky tape is sufficient to do the job. A quarter-inch hole should be drilled in the side wall at one of the bottom corners of the box.

A small tray to hold the flammable dust can be constructed of heavy kitchen-type aluminum foil. A piece of foil is cut into the form of a regular trapezoid with edge dimensions of about six-by-five-by-six-by-three centimeters. A pencil stub or similar-sized object about four centimeters long is attached (with tacks or adhesive) to what will become the bottom of the five-inch side. Overhanging foil is bent upward to form the outboard end of a shallow tray. The opposite, three-centimeter, side is bent upward to form an open trough about 1 centimeter in width. The finished object is a small tray about six centimeters long, almost flat at the wide, outboard end and formed into an open channel about one centimeter deep at the inboard end. Placed on a flat surface, the tray will have a gentle upward slope toward the outboard end. Figure 1 provides a photographic illustration of the individual parts of the apparatus described above.

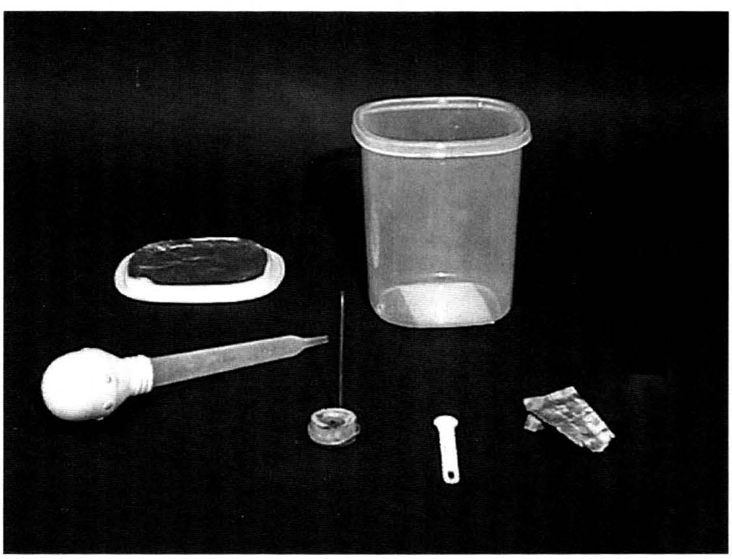

***Figure 1.** Materials used for dust explosion demonstration.*

The dimensions noted above are not critical. The objective is to contain the flammable dust in such a way that a puff of air at the inboard end will lead to dispersion of the sample into the air space of the box.

Flammable dusts of many different sorts have been involved in destructive explosions. Nevertheless, dust samples that have been held in storage for any length of time become more difficult to ignite, possibly because of agglomeration during storage or adsorption of moisture from the surroundings. Lycopodium powder, readily available from reagent suppliers, is exceptional in retaining its easy ignitibility, even after prolonged storage. It is the most satisfactory fuel for dust explosion demonstrations. Part of the reason is that its equilibrium moisture content is low as compared to cornstarch and other combustible powders that could be used.

The lycopodium dust sample, about 0.5 cm^3 in volume, is placed in the narrow end of the tray after that end has been positioned directly in front of the 1/4-inch hole drilled near a bottom corner of the food storage box (which is intended for accepting the discharge end of the turkey-baster tube). The tray should be oriented diagonally toward the opposite corner of the box.

A short candle of the type used in candle lamps, about 1/2-inch high and 1 1/2-inch diameter, serves as a convenient ignition source. It is placed on the inside bottom of the box, diagonally across from the dust sample tray. If the candle is provided with a handle, say of coat-hanger wire, it can be ignited before positioning in the box. Safety glasses should be worn, and without undue delay, the snap-on top of the container should be put in place, making sure that it is firmly seated. Inserting the discharge end of the turkey baster into the quarter-inch hole in the container wall and gently squeezing the baster's bulb can lead to immediate dispersion and ignition of the dust cloud, filling the container with a burst of flame and blowing off the snap-on top with a satisfying "pop." The candle can be repositioned a bit to one side if the air jet extinguishes it before the dust cloud is ignited.

Figure 2 shows the flame propagation rate in the appa-

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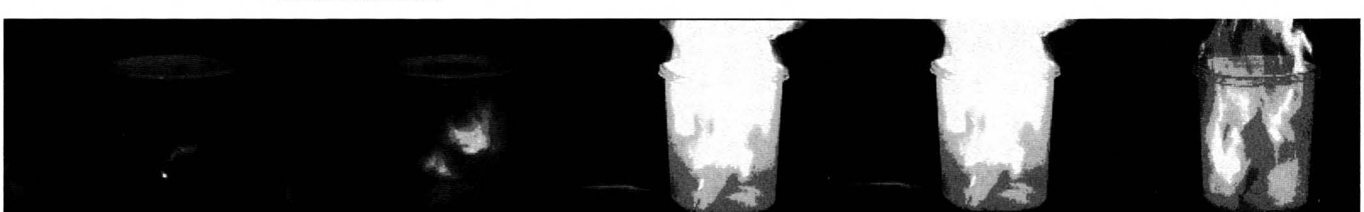

Propagation (70 ms) 140 ms 200 ms 270 ms 360 ms

***Figure 2.** Sequential photographs of explosion recorded during the demonstration.*

t time [s]
T stagnation temperature [K]
T_e temperature at the nozzle exit plane [K]
U gas velocity at the nozzle exit plane [m/s]
V internal volume of pressure vessel [m^3]
k discharge rate constant defined [1/s]
γ ratio of specific heats [–]
ρ gas density at the nozzle exit plane [kg/m3]
θ dimensionless temperature, defined as $\theta = T(t) / T(0)$

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ratus. In this experiment, the time from ignition to full involvement was on the order of (200 - 70) ms, or 130 ms for propagation through about 20 cm. This corresponds to a propagation rate of roughly 1.5 meters per second, extremely slow by explosive standards. For example, black gunpowder propagates at a rate of about 400 meters per second, while typical high explosives such as TNT propagate at about 4000 meters per second.[11]

Flammable dusts rarely, if ever, constitute a hazard in the open air. Operations capable of creating dust explosion hazards are usually conducted inside buildings such as flour mills and grain elevators, as well as in facilities associated with the manufacture and/or use of such products as edible flours, powdered sugar, metallic pigments, etc. Dust concentrations capable of ignition are reported to contain on the order of at least 30 g/m^3.[10] This is much higher in solids content than could be tolerated by human operators. For example, it has been noted that minimum flammable concentrations of most dusts would limit visibility to a meter or so. Accordingly, flammable dust-air compositions are usually found in closed processing containers or in isolated areas within a manufacturing facility. An ignition source is also required—perhaps a pilot flame, a welding spark, an electrical fault, or the like.

The original explosion may be too small to cause appreciable damage. The resulting shock wave may, however, dislodge additional dust from horizontal surfaces, cracks and crevices, storage areas, and the like. A new and perhaps larger dust cloud is formed and may be ignited by the original source or by hot embers. This cycle, typical of dust explosions, may repeat itself four or five times or more and culminate in complete destruction of the facility. Cleanliness counts in keeping control of dust explosions.

Dust explosions in closed containers are reported to generate pressure on the order of 3 to 7 atmospheres.[2] Buildings housing ordinary manufacturing facilities will not support such internal overpressures. Quite modest excess pressure, on the order of a fraction of an atmosphere, may cause roofs to rise and walls to bulge, leading to a complete collapse of the structure.[12] This collapse represents most of the energy released during the incident. Keep in mind that the initial dust explosion had only a small fraction of that energy. The dust explosion energy probably served only to move or distort structural elements upon which the building was supported. A little can do a lot.

CONCLUSION

We have provided a simple system to demonstrate the explosiveness of dusts. Students witnessing these experiments are always impressed and tend to remember this demonstration for many years thereafter. The experience creates an awareness of the explosiveness of dust and of the necessity to prevent such experiences from happening inadvertently.

AUTHOR'S NOTE

As we were preparing this paper, a high school teacher, Mr. David Barr, Cranston High School West, pointed out to us a similar experiment used during Halloween that is described on the internet.[13,14]

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