DUST EXPLOSIONS: HOW SHOULD THE INFLUENCE OF HUMIDITY BE TAKEN INTO ACCOUNT?

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In this work, the influence of humidity on dust explosions of metallic (aluminium) and organic materials (icing sugar, polyethylene and magnesium stearate) has been studied. Experiments were especially performed thanks to a 20 L explosion sphere and volume resistivity and charge decay time apparatuses. The influence of humidity has been studied by two ways: on the one hand, the dust sample was stored in a controlled workstation at constant relative humidity; on the other hand, the dry dust was dispersed in a humidity controlled atmosphere in the vessel.

As expected, various trends have been observed depending on the materials. Inhibition phenomena have been verified for polyethylene particles, whereas a more complex behaviour observed for icing sugar could be explained by an evolution of sucrose structure as a function of humidity content. Dry aluminium dust explosions in humid atmosphere show that water vapour inert the explosion. However when aluminium is stored at controlled humidity, the maximum rise of pressure rate increases with water content due to hydrogen generation. Experiments on powders volume resistivity and charge decay time have shown typical trends but have pointed out the inadequacy of various standards.

KEYWORDS: dust explosions, humidity, water activity, static electricity, standards

INTRODUCTION

Like fire and ice, humidity and dusts explosions have often been considered as antagonistic forces. A glance at case histories and statistics tends to corroborate this assertion. For instance, Count Morozzo’s account of the first quoted dust explosion in a flour warehouse in Turin on the 14th December 1785, mentioned that this accident could be attributed “to the extraordinary dryness of the corn” due to a “remarkably dry” weather (Eckhoff, 2003). Li et al. (Li, Kauffman & Sichell, 1995) also underlined that statistics on dust explosions in the United States from 1979 to 1986 clearly show that most of the accidents occurred during winter months when the atmosphere has the lowest humidity content.

However, the relationship between dust explosivity and powders moisture content (and thus relative humidity) is not as univocal as it superficially seems. In particular, fermentation for grain dusts and oxidation-reduction reactions of metal powders with water are both processes, generating combustible gas, which should not be neglected in risk analyses (Otsuka & Itagaki, 2004).

Despite these facts, the overwhelming majority of standards and procedures related to dust explosion characterisation neglects the impact of humidity and only specifies that the relative humidity should be checked and noted down, as for instance IEC 1241-2-1 (MIT) or IEC-2-3 (MIE).

In this work, the effects of both water activity and ambient humidity on dust explosions characteristics have been checked. Natural and synthetic organic compounds but also metal powders have been tested. The proportion of electrostatic discharges as ignition sources in dust explosion accidents being significant (Planas-Cuchi, Montiel & Casal, 1997), notably for plastic compounds, the influence of humidity on electrostatic properties has also been investigated.

EXPERIMENTAL EQUIPMENTS AND TESTS PROCEDURES

SAMPLES CHARACTERISTICS AND PREPARATION

Experiments were carried out with four materials chosen for their various natures: icing sugar – a natural organic powder, polyethylene dust and magnesium stearate – synthetic organic compounds and aluminium powder, a metal. Aluminium powders were provided by Goodfellow with 99% purity and a specific maximum particle size of 15 μm. Icing sugar was provided by Erstein and polyethylene (PE) powders were provided by Innovene; various particle-size distributions were obtained by sieving. Magnesium stearate was supplied by Sigma-Aldrich. The particle-size distribution of the dusts was determined by using a laser diffraction analyzer (Mastersizer, Malvern Instrument). The samples were characterized by the d10, d50 and d90 quantiles of the volumetric distribution as indicated on table 1; the d3 diameter, being defined as the size at which x% of the particles are smaller. The Sauter mean diameter d3,2, defined as the diameter of a sphere having the same volume to surface area ratio as the particle, is also indicated on Table 1.

Scanning electron microscope (SEM) was also performed on powders samples to characterize the particles shapes and the surface roughness (Figure 1).
Aluminium particles are rather ellipsoidal than spherical and their surface is quite smooth. Icing sugar is composed of crystal-shape particles, whereas magnesium stearate powder looks like flakes. Polyethylene pellets are rather spherical with a porous and highly irregular surface.

The samples were systematically dried at 50°C under vacuum during two hours before handling. Two methods were used to demonstrate the influence of relative humidity (RH) on aluminium dust explosions: i) the dry dust was dispersed in a humidity controlled atmosphere in the explosion vessel, or ii) the dust sample was stored in a controlled workstation (glove box) at constant relative humidity during a sufficient period of time allowing the equilibrium to be reached.

The relation between the water activity – ratio between the vapour pressure of water in the compound to the vapour pressure of distilled water under the same conditions; similar to the relative humidity in percent divided by 100 – and the water content in the powder is called adsorption isotherm. It was characterized by using an electromagnetic suspension microbalance (Figure 2). The time to equilibrium was also determined.

### EXPLOSION SENSITIVITY

Even if this study does not specifically deal with the explosion sensitivity, the minimum ignition energy (MIE), minimum ignition temperature (MIT) and minimum explosive concentration (MEC) have been determined on dried samples. The measurement of minimum ignition temperature has been carried out thanks to a Godbert-Greenwald furnace (Chilworth Technology), whereas the minimum ignition energy and minimum explosive concentration have been determined by using a modified Hartmann tube (Kühner AG) (Siwek & Cesana, 1995). Tests were carried out in accordance with the principles of IEC standards 1241-2-1 and 1241-2-3. The results of the various tests are listed in Table 2. The ignition sensitivity index of aluminium dusts with 7 μm d50 could be calculated by the following relationship (Jacobson, Cooper & Nagy, 1965):

\[
I_{\text{Sens}} = \frac{(\text{MIE} \cdot \text{MIT} \cdot \text{MEC})_{\text{Pittsburgh coal dust}}}{(\text{MIE} \cdot \text{MIT} \cdot \text{MEC})_{\text{Sample dust}}}
\]

Table 2 shows that the aluminium, icing sugar and mainly magnesium stearate could be considered as highly ignitable dusts, whereas polyethylene has a far lower ignition sensitivity. It has been demonstrated that humidity tends to lower the ignition sensitivity of organic materials, depending on the hydrophobic or hydrophilic nature. MIT and MEC especially increase when the water content of the dust raises (Nagy & Verakis, 1983) (Nifuku et al., 2006).

### EXPLOSION SEVERITY

The explosion severity parameters \(P_{\text{max}}\), maximum pressure, and \((dP/dt)_{\text{max}}\), maximum rate of pressure rise, have been determined in a 20 L apparatus (Kühner AG) (Calle’ et al. 2005). The test chamber is a hollow sphere made of stainless steel. A cooling water jacket dissipates the heat of the explosion. During a test, the dust is dispersed into the sphere from a pressurised storage chamber via the outlet valve and a disperser. Tests have been performed with two pyrotechnic ignitors of 5 kJ each as ignition source. The explosion pressure is recorded as a function of time using piezoelectric pressure sensors. The dust concentration is then varied over a 60 to 3000 g/m³ range. This apparatus also allows the determination of minimum explosive concentration, below which explosion is not possible. Tests were carried out according to ISO 6184-1.

Some modifications were made on the sphere: i) a thermocouple was introduced in the centre of the sphere to record the temperature during an explosion; ii) the temperature of the water outlet was also recorded, iii) a system of gaseous effluents treatment was added, iv) the sphere has been grounded to avoid uncontrolled electrostatic discharges. In order to control the relative humidity, the 20 L sphere has also been modified with an injection system which allows the vaporisation of a precise amount of water in the vessel before ignition. For operating temperatures lower than water boiling point, the injected water

### Table 1. Particles sizes of the powders

<table>
<thead>
<tr>
<th>Samples</th>
<th>(d_{10}) (μm)</th>
<th>(d_{50}) (μm)</th>
<th>(d_{90}) (μm)</th>
<th>(d_{1,3}) (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>3</td>
<td>7</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td>Icing sugar A</td>
<td>7</td>
<td>22</td>
<td>41</td>
<td>7</td>
</tr>
<tr>
<td>Icing sugar B</td>
<td>17</td>
<td>45</td>
<td>76</td>
<td>12</td>
</tr>
<tr>
<td>Magnesium stearate</td>
<td>3</td>
<td>6</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>34</td>
<td>136</td>
<td>249</td>
<td>58</td>
</tr>
</tbody>
</table>
content ranged from 0 to the vapour saturated pressure. Attention should be paid to the increase of temperature (up to 360°C) due to the 10 kJ ignition source. Even if water is introduced over the saturation volume (0.28 mL), the remaining liquid could be vaporized during ignition and before flame propagation. The pressure rise induced by the ignition source is systematically subtracted from the overall pressure.

ELECTROSTATIC HAZARDS QUANTIFICATION

The knowledge of the volume resistivity ($\Omega_m$) and the charge decay time of a powder could bring valuable information on its electrostatic hazards (Laurent, 2003). The volume resistivity (in $\Omega.m$) of a material is the electrical resistance across a cube of unit cross sectional area and unit length. The volume resistivity is determined by placing the powder sample in a resistivity cell comprising two electrodes between which an electric current may be passed through the sample (Chilworth Technology Ltd). Measurements were carried out according to IEC standard 1241-2-2.

Charge decay time is measured by recording the residual charge on the powder as a function of time as it is conducted to earth. The decay time ($\tau$) is then defined as the characteristic time taken for the charge to decrease to $1/e$ (0.37) of its initial value. It was measured by a static monitor “field mill” instrument JCI 140 (John Chubb Instrumentation). However, powders seldom behave in this way and if the decay is not a true exponential, such as where the material is non-ohmic, thus there will not be a simple relationship between the relaxation time and the decay time. Tests were carried out according to BS7506 standard.

Temperature and humidity greatly affect electrical flow and adhesion properties of powders. For this reason it is essential to perform many electrostatic measurements under controlled temperature and humidity conditions. The temperature inside our glove box chamber can be controlled between $-10$ and $80^\circ\text{C}$, and the relative humidity between 0.1 and 99.9%.

RESULTS AND DISCUSSION

HUMIDITY AND STATIC ELECTRICITY

It is common knowledge that the presence of static electricity could be significantly reduced by increasing the relative humidity up to 60%. However true this assertion is, this solution can be contestable because it also modifies the powders properties, causes equipment problems and introduces biological contaminants into the powder and equipment.

Figure 3 shows the relative humidity dependency on volume resistivity at 25°C. Behaviours of icing and magnesium stearate are clearly different, owing to the hydrophilic nature of sugar and hydrophobic one of magnesium stearate. Thus, the volume resistivity of icing sugar is 10 times lower at 30% RH than at 15% RH; whereas the resistivity of magnesium stearate is not humidity dependent. The sorption isotherms show no significant differences between water sorption on icing sugar and on magnesium stearate (up to 75% RH – figure 2). However, a chemical modification of the particles surface is confirmed by TDA for icing sugar.

Figure 4 present the relative humidity dependency on the charge decay time at 25°C. The icing sugar decay time is about 10 seconds for 40% humidity while it is equal to 1 hour for 15% humidity. For the magnesium stearate the charge decay time falls from 135000 seconds (more than 37 hours) at 17% RH to 60000 seconds (16.6 hours) at 75% RH. Even if an influence is henceforth noteworthy on magnesium stearate, the sensitivity to water activity is once again more pronounced on sugar.

The previously quoted standards, especially the one concerning volume resistivity, only specify that a powder

![Figure 2. Adsorption isotherms of a) icing sugar, PE b) aluminium and magnesium stearate at 25°C](image-url)

### Table 2. Explosion sensitivity of the powders

<table>
<thead>
<tr>
<th>Samples – $d_{50}$ (µm)</th>
<th>MIT (°C)</th>
<th>MIE (mJ)</th>
<th>MEC (g.m$^{-3}$)</th>
<th>$I_{\text{cross}}$</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium – 7</td>
<td>900</td>
<td>13</td>
<td>30</td>
<td>5.7</td>
<td>Severe</td>
</tr>
<tr>
<td>Icing sugar – 22</td>
<td>380</td>
<td>18</td>
<td>50</td>
<td>5.9</td>
<td>Severe</td>
</tr>
<tr>
<td>Magnesium stearate – 6</td>
<td>420</td>
<td>3</td>
<td>30</td>
<td>53.2</td>
<td>Severe</td>
</tr>
<tr>
<td>Polyethylene – 136</td>
<td>480</td>
<td>500</td>
<td>60</td>
<td>0.1</td>
<td>Weak</td>
</tr>
</tbody>
</table>
The sample can “be tested directly” (without conditioning). The previous results show that it is indispensable to work at the process most representative humidity and that experiments have to be carried out more accurately and carefully than specify by the existing standards.

EFFECT OF HUMIDITY ON EXPLOSION SEVERITY

The explosion severities of three dusts have been studied. As a function of their nature, three distinct behaviours have been identified.

No considerable variations of icing sugar explosivity have been observed as a function of the particles moisture; however, significant and reproducible trends have been noticed. From 0 to 30% RH (from 0 to 0.34% moisture content), both maximum pressure and rate of pressure rise slightly increase, whereas when the water activity raises to 75% RH (1.7% moisture content, before irreversible agglomeration at 80%) the dust explosivity significantly drops (figure 5). Those behaviours have been observed for various concentrations and particles-size distribution.

As regard to thermogravimetric and thermo-differential analyses, a slight change in icing sugar thermal response—and thus structure—as a function of the storage humidity has been demonstrated. The hypothesis of a sugar maturation and sucrose inversion (from sucrose to glucose and fructose), leading to greater particles ignitability, could be put forward (Traore et al., 2004). Humidity, which influences interfacial gas adsorption and desorption generates an oxygen saturated “sirup” layer on particle surfaces, increasing the liability to spontaneous combustion. This surface modification promotes the combustion kinetics of sugar particles. This impact will only be perceptible for low humidities and gives way to water inhibition phenomena when the moisture content increases. The previous trends are not observed when the explosivity of dry icing sugar is tested in a humid atmosphere.

Both moisture content of the particles and humidity of the explosion atmosphere have an influence on polyethylene dusts explosion. Figure 6 shows that both maximum explosion pressure and rate of pressure rise tends to lower when the relative humidity increases. The calculation of adiabatic flame temperature in presence and absence of water demonstrates that the injection of water up to saturation implies a drop of maximum pressure of approximately 0.3 bar, which corresponds to the observed decrease. The

Figure 3. Influence of the relative humidity on the volume resistivity (25°C) on icing sugar – 22 μm (a) and on magnesium stearate – 6 μm (b)

Figure 4. Influence of the relative humidity on the charge decay time (25°C) on icing sugar – 22 μm (a) and on magnesium stearate – 6 μm (b)
effect of humidity on polyethylene explosion is thus essentially due to heat consumption by water vaporization; phenomenon which is more important since the water content in polyethylene dust is significant (figure 2).

It should be pointed out that, a slight pressure increase could be expected for high water volumes due to water vaporization. This effect would induce a 6% rise of the maximum pressure for a 1 ml water injection and could explain the pressure increase noticed for water volumes greater than saturation.

Experiments were also performed with aluminium particles with a mass median diameter of 7 μm. Figure 7a presents the maximum pressure as a function of the relative humidity of the dust storage. It could be noticed that storage conditions have a significant effect on the maximum explosion pressure, especially at 60 and 76% of relative humidity. This trend is even more noticeable on the maximum rate of pressure rise, which raises from 1530 bar.s⁻¹ for dry powders to 2100 and 2150 bar.s⁻¹ at respectively 60 and 76% RH for 250 g.m⁻³ dusts concentration.

It should then been pointed out that aluminium metal is amphoteric and that its reaction with water or moisture liberates flammable gas as hydrogen. Thus, if the protective layer of alumina is broken, a rapid oxidation reaction occurs generating a large amount of heat. The promotion of explosion violence is thus probably due to the following reaction between water and aluminium (Kwok, Fouchard, Turcotte, Lightfoot, Bowes & Jones, 2002):

\[
2Al(s) + 3H_2O(g) \rightarrow Al_2O_3(s) + 3H_2(g)
\]

The sorption isotherm represented on figure 2 supports this theory and it could be seen that 0.45 g of water are adsorbed onto 100 g of aluminium as soon as the water activity exceeds 0.1.

Explosions of dry aluminium were also carried out in humid atmosphere by injecting a specific volume of water. Here, water molecules have not enough time to adsorb onto aluminium particles surface. In fact the contact between water molecules and aluminium particles lasts the
time of the combustion (from 20 to 70 ms); whereas the time
of sorption equilibrium is about two hours. This method
allows the verification of the inhibiting effect of water on
materials ignition without modifying the physico-chemical
structure of the dust.

Water amounts are very low (the saturation volume is
about 0.3 ml) but when injected in the sphere, they reduce
the explosion pressures from at least 1 bar at saturation
(Figure 7 b). Nevertheless, considering the drop of pressure
due to the water enthalpy of vaporization does not seem to
be sufficient to explain the observed reduction of explosion
pressure. The maximum rate of pressure rise also decreases
for large water volumes from 900 (dry powder) to 400
bar.s$^{-2}$ for 250 g.m$^{-3}$ dusts concentration.

The presence of water also seems to hinder the particles
ignition, leads to aluminum dusts agglomeration and
slows down the oxidation kinetics.

It emerges from this study that the influence of water
on aluminum dusts explosivity could be decoupled: when
water adsorption occurs, hydrogen generation leads to an
augmentation of the explosion severity, whereas an inhibit-
ing effect could be put forward when the effective contact
time between water and aluminum is reduced to the
explosion duration.

CONCLUSIONS

Depending on their chemical nature, the relative humidity
and thus the moisture content of powders could inhibit or
promote the dusts ignitability and explosion severity.
These influences are sometimes very strong and lead to
explosion risks higher than for the dry powder.

However, it should be underlined that standards often
neglect the impact this essential parameter. As an example,
ISO 6184-1 standard specifies that the determination of the
dust explosion indices should be carried out at humidity
lower than 10%; which is not the worst case scenario
especially for some metallic powders. As a conclusion, a
peculiar attention should be paid to this parameter and stan-
dards should sometimes be bypassed or modified to take
the influence of humidity into account.

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