On the determination of the minimum ignition temperature for dust/air mixtures

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The research presented in this paper focuses on the prevention and mitigation of dust explosions. The main objective is to demonstrate the applicability of a theoretical/numerical approach to evaluate the most important explosion parameters for characterizing the risk and hazard of dusts.

In a previous paper (Di Benedetto and Russo, 2007), we have proposed a model to compute the deflagration index of dusts. The model is based on the assumption that the pyrolysis/devolatilization step is very fast and, thus, gas combustion controls dust explosion (which is true at diameter lower than a critical value). Under the same hypothesis, in the present work, we compute the minimum ignition temperature for polyethylene dust at different dust concentrations in air. We also compare the computed data with experimental results available in the literature, thus validating the model.

1. Introduction

Dust explosion hazards are common in industries like coal mining, storage and processing of agricultural products (i.e., starch, flour, sugar, cocoa) and organic dusts (i.e., drugs, dyestuffs, plastics), and the manufacture of metal powders (i.e., aluminium, magnesium). Various unit operations involving combustible solids, such as grinding, drying, dust collection and pneumatic and other modes of transportation, are always exposed to explosion risk.

In order to prevent and mitigate the risk coming from these operations, the explosion parameters, such as maximum pressure, maximum rate of pressure rise and deflagration index, minimum explosible dust concentration and minimum ignition temperature, have to be determined. Among these parameters, the minimum ignition temperature (MIT) at which dust clouds ignite is required to prevent the explosion risk arising from the presence of hot surfaces.

Hot surfaces capable of igniting dust clouds exist in a number of situations in industry (furnaces and burners, dryers of various kinds). In addition, hot surfaces can be generated accidentally by overheating bearings and other mechanical parts.

If an explosible dust cloud is generated in some uncontrolled way in the proximity of a hot surface with a temperature above the actual minimum ignition temperature, a dust explosion can result. As a consequence, in the prevention and mitigation of dust explosions, it is important to know the minimum ignition temperature of dusts in order to take adequate precautions to ensure that hot surface temperature does not reach this value.

1.1 Minimum ignition temperature of dust clouds

The minimum ignition temperature of a specific dust is defined as the minimum air temperature for which the flame due to combustion of the dust particles is just observed. The evaluation of the minimum ignition temperature is usually performed by oven tests as described in ASTM E1491-06 (2006). In this ASTM standard test method, dust is dispersed into a heated furnace set at a predetermined temperature. The dust cloud is exposed to the heated furnace walls for several seconds. A visible flame exiting the furnace provides evidence for ignition.

The dust concentration and temperature are systematically varied to find the lowest temperature at which auto-ignition occurs for the most easily ignited dust concentration. In ASTM E1491-06 (2006), four different furnaces are described as suitable for MIT measurement: the 0.27-L Godbert–Greenwald Furnace, the 0.35-L BAM Oven, the 1.2-L Bureau of Mines Furnace and the 6.8-L Bureau of Mines Furnace. Each furnace yields slightly different MIT data, with the largest deviations occurring at the greatest MIT values. However, the lower MIT range is of more practical importance and here the agreement is much better.

For a given dust, these data are influenced by concentration of dust/air mixture, moisture content and dust particle size. Careful studies of the dependence on particle size for several dusts revealed the existence of characteristic diameters below which the MIT becomes size invariant. As an example, the MIT of polyethylene becomes independent of particle size for diameters below 80 µm (Conti and Hertzberg, 1987). The existence of similar characteristic diameters has also been found for the lean limits of flammability.

The test data developed from these test methods can be used to limit the temperature to which a dust cloud is exposed so as to prevent ignition of the cloud. Because of the short duration of the test, the data obtained are most applicable to industrial equipment where dust is present as a cloud for a short time.

In the past, results from small-scale laboratory tests were often applied directly to industrial plant design. However, it has been known for some time that minimum ignition temperatures of dust clouds vary significantly with scale (Wolanski, 1992).

As shown by Eckhoff (2003), care must be taken when using the data coming from these tests. The minimum ignition temperature is a strong function of the residence time of the dust in the furnace. As a consequence, it is not straightforward to absolutely define a minimum ignition temperature from such experiments.

The development of reliable mathematical models for predicting the minimum ignition temperature becomes essential to overcome these problems.

Up to now, many models have been proposed for the computation of this parameter (Cassel and Liebman, 1959; Mitsui and Tanaka, 1973; Krishna and Berlad, 1980; Zhang and Wall, 1993). They are mainly based on the assumption that oxidation of the dust particle is a surface phenomenon and reaction on the particle surface is responsible for auto-ignition of the dust cloud.

This assumption is valid for inorganic dusts but it fails for organic dusts, as also highlighted by Mittal and Guha (1997). These authors developed a model for the calculation of the minimum ignition temperature of polyethylene, simulating the conditions in the Godbert-Greenwald furnace. The model assumes that combustion of the gas products coming from the devolatilization of the dust particle is the controlling step. They calculated the MIT as the temperature at which the heat produced by reactions is equal to the heat losses toward the environment. This calculation is therefore related to a thermal explosion ignition.

Beside thermal explosion, radical explosion may occur. At a fixed value of dust temperature, the volatiles produced may react giving rise to a radical pool which eventually leads to ignition of the gas/air cloud. Since thermal explosion and radical explosion occur simultaneously, it is fundamental to simulate both phenomena.

1.2 Aim of the work

In a previous paper (Di Benedetto and Russo, 2007), we have proposed a model to compute the deflagration index of dusts.

The model is based on a two-stage oxidation mechanism involving devolatilization/decomposition of the solid particle and homogeneous oxidation of the volatile combustible products. It assumes that the pyrolysis/devolatilization step is very fast and, thus, gas combustion controls dust explosion (which is true at diameter lower than a critical value). The step of combustion of the volatiles is modeled by implementing a detailed reaction mechanism.

In this paper, we use the same approach for the computation of the minimum ignition temperature of dust clouds. By means of this model, we simulate both thermal and radical ignition of dust clouds considering combustion/explosion of the volatiles as the controlling step. We apply the model to polyethylene dust explosion.

2. The Model

The model equations are the unsteady conservation equations for mass, species and energy in a closed reactor, which read:

Mass balance equation

$$\frac{d(V\rho)}{dt} = 0 \qquad (1)$$

Mass balance equation on species i

$$\frac{d(V\rho y_i)}{dt} = -r_i V \qquad \text{i} = 1, \text{....}, \text{N-1} \qquad (2)$$

Energy balance equation

$$\frac{d(VC_p T\rho)}{dt} = \sum_{i=1,N} (-\Delta H_i) r_i V \qquad (3)$$

The initial conditions are written as follows:

$$t = 0 \quad \rho = \rho_{in} \tag{4}$$

$$t = 0 \quad y_i = y_{i,in} \tag{5}$$

$$t = 0 \quad T = T_{in} \tag{6}$$

The composition of the volatiles for polyethylene dust is obtained from literature data. In particular, the best agreement between simulation and experimental results is found by using the composition data of Font et al. (1995) (high density polyethylene, HDPE) (Table 1).

Table 1 Composition of the volatiles of polyethylene dust (Font et al.,1995)

T (°C)	CH_4 (wt%)	C_2H_4 (wt%)	C_3H_8 (wt%)	C_4H_{10} (wt%)
800	5.66	76.83	8.79	8.72

The homogeneous combustion process of the volatiles is simulated by using the GRI-Mech 3.0 (Smith et al., 1999) detailed reaction mechanism. This mechanism is implemented in the CHEMKIN 4.1.1 module (www.reactiondesign.com) of the closed vessel to calculate the ignition delay time as a function of the initial temperature of the mixture.

Simulations are performed by changing the initial conditions of temperature for different dust concentrations in air.

3. Results

In Figure 1, the temperature time history is shown as computed during the ignition process of the polyethylene with dust concentration in air equal to 300 g/m^3 and initial temperature of 750 K.

In Figure 2, the model results are reported in terms of minimum ignition temperature as a function of the residence time for different dust concentrations (80, 300 and 500 g/m^3). As would be expected, the minimum ignition temperature decreases on increasing the residence time and the dust concentration.

The experimental Godbert-Greenwald dust cloud ignition temperatures for polyethylene are plotted in Figure 3 versus the median dust diameter (Eckhoff, 2003; GESTIS-DUST-EX database; Mittal and Guha, 1997).

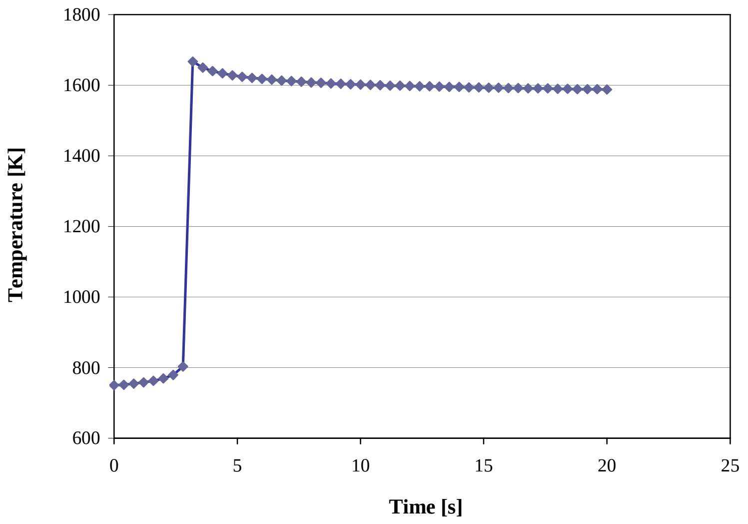

Figure 1. Temperature time history during the ignition process of polyethylene dust (dust concentration = 300 g/m^3, initial temperature = 750 K).

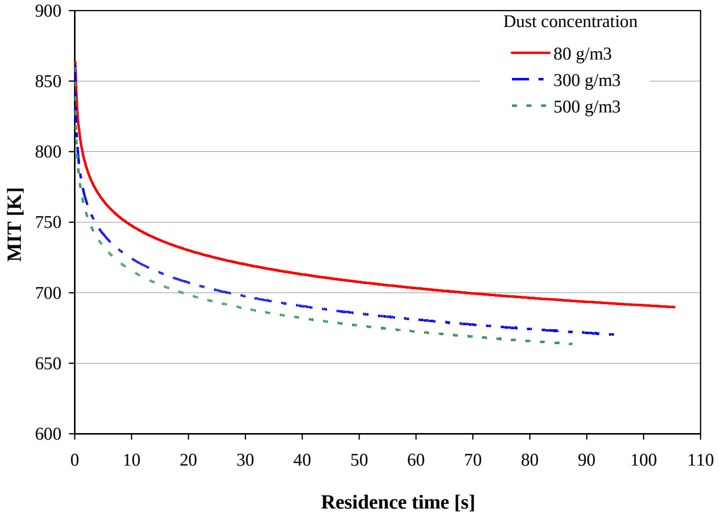

Figure 2 – Calculated MIT for polyethylene as a function of the residence time at different dust concentrations.

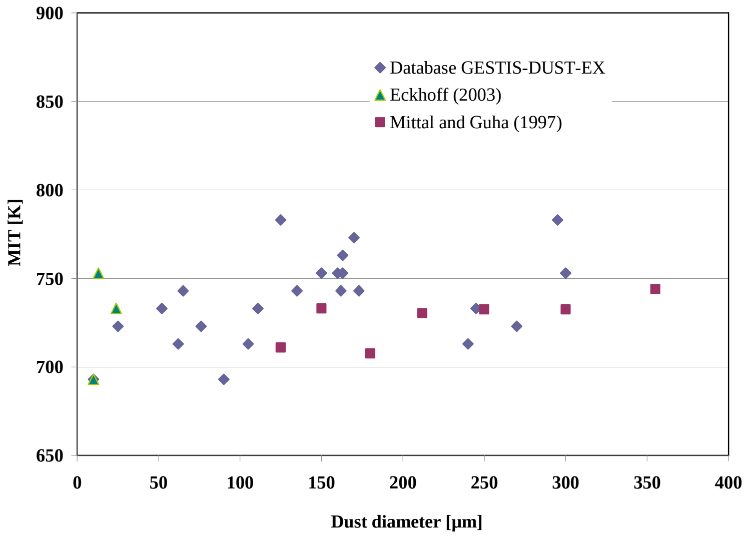

Figure 3 – Experimental MIT for polyethylene as a function of the dust diameter.

The comparison between computed and experimental data shows that the model is able to predict the lowest value of MIT (equal to about 690 K) which corresponds to particle diameters lower than the polyethylene critical diameter.

4. Conclusions

The model developed by Di Benedetto and Russo (2007) for the computation of the deflagration index of dusts has been extended to calculate the minimum ignition temperature. The agreement with experimental data is quite good, suggesting the validity of the hypothesis on which the model is based. Further comparisons with experimental data are needed to complete the model validation.

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