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On the effect of initial pressure on the minimum explosive concentration of dust in air

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ABSTRACT

Standard explosion tests were performed in the 20 l sphere to measure the minimum explosion concentration (MEC) of nicotinic acid in air at different initial pressures. CFD simulations were also run in order to gain insight into the experimental results particularly in terms of effects of initial pressure on turbulent flow field, and dust dispersion and feeding efficiency.

According to the literature results, it has been found that MEC increases with increasing initial pressure. This trend has been attributed to the decrease of the burning velocity with pressure.

It has been shown, via CFD simulations, that the actual dust concentration in the whole vessel and at the center of the vessel, where ignition is provided, is much lower than the nominal dust concentration. Thus, the MEC values measured in the sphere on the basis of the nominal dust concentration are misleading. We computed a scale factor to correct the "nominal" MEC, $MEC_{Nominal}$, to the "actual" MEC, MEC_{Actual}. In particular, we may suggest that, when measuring the MEC in the standard 20 l apparatus, MEC_{Actual} may be obtained by multiplying $MEC_{Nominal}$ by the ratio, γ, between the dust concentration in the center of the vessel (@ $t = 60$ ms) and the nominal dust concentration: $MEC_{Actual} = \gamma\ MEC_{Nominal}$. MEC_{Actual} is much less sensitive to variations in initial pressure than $MEC_{Nominal}$.

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1. Introduction

In chemical and process industries, many units handling flammable dusts operate at pressure different from 1 atm. Recent examples are chemical processes involving biomasses [3] and additive manufacturing technology [4]. Furthermore, in transfer and storage operations, dusts may experience pressures different from 1 atm. Transfer of dusts may be performed through the powder transfer system (PTS), which is based on pressure gradient rather than gravity [11], or by the pneumatic transport at high pressure and low velocity or low pressure and high velocity. Dust collection in dust extraction and filtration may operate under vacuum or under pressure higher than the atmospheric value.

For the design of prevention and mitigation measures in the chemical and process industries involving flammable dusts, reliable safety data are required [5]. In most material safety sheets and databases, flammability and explosion parameters are given as measured at pressure equal to 1 atm. However, to safely handle dusts, such parameters have to be measured at the actual operating pressure.

From the few data available in the literature, it turns out that the minimum explosion concentration (MEC) increases with increasing pressure [12,14,15,17]. Wiemann [17] measured the MEC values of brown coal in air at pressure up to 3 atm. He found a linear increase of MEC with pressure. Hertzberg et al. [12] measured the MEC values for coal/ and polyethylene/air mixtures at changing pressure in the range 0.4–2.5 atm. They explained the observed linear trend of MEC with pressure by assuming that, on increasing pressure, the production of volatiles and the mixing efficiency between volatiles and air in the sphere decrease. More recently, Pilão et al. [14,15] measured the MEC values of cork/air mixtures in the pressure range 0.9–2.1 atm, also finding a linearly increasing trend. They attributed the increase of MEC to the decrease in O_2 content with increasing initial pressure.

All these measurements were performed in spherical or near spherical vessels of about 20 l according to the standard procedure. In recent papers, we have shown, via CFD simulations, that turbulence and dust dispersion are not uniform inside the sphere [6] and are affected by several parameters such as the dust size [7] and the dust concentration [8]. Measurements of flammability and explosion parameters are significantly affected by the conditions of turbulence and dust dispersion generated inside the vessel. Indeed, the pre-ignition turbulence may affect

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the flame propagation speed as well as the efficiencies of dust feeding and mixing.

We have also shown that the dust particles may undergo breakage when fed from the dust container to the vessel, and that the particle breakage is dependent on pressure [16].

In this work, we investigated the effect of initial pressure on the dust breakage, the pre-ignition turbulence, the dust dispersion and feeding efficiency, and the resulting MEC values for nicotinic acid/air mixtures. The MEC values were measured in the 20 l sphere according to the standard procedure by changing the initial pressure from 0.6 atm up to 2.8 atm. CFD simulations of the evolution of fluid flow and dust dispersion inside the sphere at changing the initial pressure were also performed to quantify the spatio-temporal distribution of turbulence kinetic energy and dust concentration.

2. Methods

2.1. Experimental apparatus and procedure

Explosion tests were performed adopting the procedure reported in the ASTM E1226 standard and using a 20 l combustion chamber manufactured by Adolf Kuhner (CH). A scheme of the device used in the present investigation is reported in Fig. 1.

The bomb (B), a combustion chamber made by stainless steel capable to withstand 30 atm of overpressure, is surrounded by a jacket for the control of the wall temperature (service fluid: water, controlled using a criothermostat Julabo CF31). At the bottom of the sphere, a rebound nozzle (RN) is placed for the dispersion of the dust/air mixture. This element is connected to a dust sample container (SC, Volume = 0.6 l), which is normally pressurized with synthetic air at 21 atm (operating the inlet valve V_1). The dust/air cloud is formed by opening the electro-pneumatic valve placed between the sphere and the sample container (V_2). After a delay of 60 ms from the outlet valve opening, explosion is triggered by an inductive electric spark generated between two tungsten roads (diameter 2 mm, 6 mm spaced) located at the center of the sphere using a high voltage transformer (KSEP 320) capable to provide an output voltage of 15.000 V. Tests were also performed by using two chemical igniters (2 × 5 kJ ignition energy). Explosion pressures were measured by means of a couple of piezoelectric transducers (PT_1 and PT_2, Kistler Type 701A tranducers) coupled with the corresponding charge amplifiers (Kistler Type 5041B).

All the experiments were performed on samples of nicotinic acid dispersed in the bomb by varying both the initial concentration of dust and the pressure at the triggering of the explosion (P_{sphere}). The initial pressure inside the bomb was set by varying the pre-evacuation pressure, which was adjusted to the desired value by means of the air (V_3) and vacuum (V_5) valves. After that, the dust was fed into the sphere by operating the outlet valve realizing values of initial pressure, P_{sphere}, varying from 0.6 atm up to 2.8 atm (this is the typical pressure range for industrial processes involving dust storage and handling). For vacuum, a Vacuubrand RZ9 vacuum pump was used. P_{sphere} was measured using the digital manometer M (model LAB DMM DFP manufactured by AEP, transducer with a measurement range: - 1.0 to 5.0 barg).

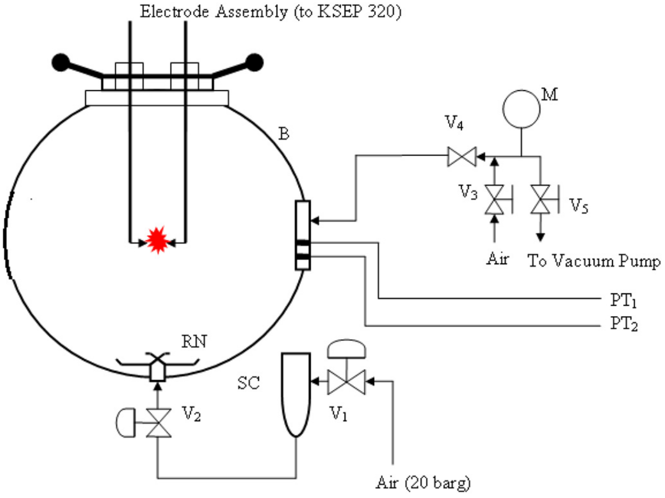

Fig. 1. Scheme of the device used in the present investigation. B: Explosion Bomb; RN: Rebound Nozzle; SC: Sample Container; V_1, …, V_6: Valves; PT_1, PT_2: Piezoelectric Pressure Transducers; M: Digital Manometer.

For each experimental condition, the tests were carried out in triplicate. An explosive event was considered taking place by applying the pressure criterion described in the ASTM E918 standard [2]: a flame propagation is considered to occur if the ratio of the maximum absolute pressure recorded during the test with powder to the maximum initial absolute pressure recorded during the corresponding blind run (a test carried out in the same conditions but without powder) is >1.07. The same criterion has been considered both in the case of electric spark and in the case of chemical igniters.

Nicotinic acid (CAS: 59-67-6, purity ≥98 w/w %) was provided by Sigma Aldrich. Particle distributions were determined using a laser granulometer Mastersizer 2000 (measuring range: 0.02 to 2000 μm) under stirring (3500 rpm) and, to avoid particle agglomeration, under ultrasounds (ethyl ether was used as dispersant medium). From these measurements, nicotinic acid particle mode diameter resulted equal to 26 μm.

The effect of initial pressure on the particle fragmentation was assessed dispersing 10 g of nicotinic acid in the desired conditions without triggering the explosion. After the dispersion of the sample, and waiting 5–10 min to allow the particle settling, the bomb was opened, the powder collected and submitted to granulometric analysis.

2.2. CFD model

In this work, we used the CFD model previously developed and validated for the 20 l sphere equipped with both the rebound nozzle [6] and the perforated annular nozzle [9]. Briefly, the model equations for the fluid flow are the time-averaged Navier-Stokes equations (Eulerian approach) written in polar coordinates. The standard k-ε model was used for the turbulence closure [13]. The Discrete Phase Model (DPM) was used to solve the flow of the solid phase (Lagrangian approach). Two-way interaction was assumed between the fluid phase and the solid particles (i.e., the particle-particle collisions were neglected) [10]. The gravitational force was included in the momentum balance equation of the DPM.

The governing fluid flow equations were discretized using a finite-volume formulation on a three-dimensional non-uniform unstructured grid. The computational domain and the grid are shown in Fig. 2.

The spatial discretization of the model equations used first order schemes for convective terms and second order schemes for diffusion terms. First-order time integration was used to discretize temporal derivatives with a time step of $1 \cdot 10^{-4}$ s.

The DPM is described by ordinary differential equations. For particle tracking, an automated scheme was adopted which provides a mechanism to switch in an automated fashion between numerically stable lower order schemes (when the particle reaches hydrodynamic equilibrium) and higher order schemes (when the particle is far from hydrodynamic equilibrium), which are stable only in a limited range. The Euler integration was chosen as lower order scheme, and the semi-implicit trapezoidal integration was chosen as higher order scheme. The particle tracking integration time step was taken equal to the fluid flow time step ($1 \cdot 10^{-4}$ s).

Parallel calculations were performed by means of the segregated pressure-based solver of the code ANSYS Fluent (ANSYS Fluent Theory Guide, Release 15.0, [1]). The Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) was used to solve the pressure-velocity coupling. In order to achieve convergence, all residuals were set equal to $1 \cdot 10^{-6}$.

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