ON THE FEATURES OF DUST EXPLOSIONS

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The research presented in this paper focuses on the importance of the prevention and mitigation of dust explosions by knowing the effect of single and combined parameters on the explosion severity. Experiments and a companion modelling study were conducted at varying the size fractions, the ignition source, the initial turbulence level, the concentration of flammable gas/vapour. The results quantitatively show the increased hazard posed by fine particle sizes of dust and admixture of flammable gas to a combustible dust. The effect of turbulence on deflagration index is minor in standard test conditions, while it is significant at high initial turbulence level. The model proposed gives a good prediction of the deflagration index at varying the dust diameter.

1. INTRODUCTION

When dust explosions are considered, five requirements are needed (Abbasi and Abbasi, 2007): 1) Fuel – combustible dust ; 2) Oxidizer – usually air; 3) Ignition source; 4) Dispersion / mixing of the combustible in the air; 5) Confinement. When all these requirements are satisfied (i.e. a flammable mixture of dust and air in the right proportion and in a confined space is ignited) the explosion occurs and a propagation of the flame across the cloud takes place. The velocity of flame propagation and then the violence and the severity of explosion depends on several factors such as the nature of dust, the dust particle size, and the nature of combustion by-products.

The severity of dust explosions is usually quantified by the thermo-kinetic parameters such as the maximum overpressure attained during an explosion (P_{max}) and the deflagration index (K_{St}). The evaluation (either experimental or theoretical) of these parameters is a fundamental step for sizing protection and mitigation systems against dust explosions, as they are used in the guidelines to protect and mitigate equipments from dust explosions (NFPA, 2002).

The severity of explosion is affected by several factors: chemical composition of the fuel, moisture content, initial pressure, temperature and turbulence, distributions of particle sizes and shapes of dust particles, agglomeration of dust particles, ignition energy and location of the ignition point (Eckhoff, 2003). From a fundamental perspective, these effects are relatively well-known and have been the subject of investigation worldwide.

As concern the effect of particle size, it is widely accepted that at particle size higher than 500 μm dusts are not explosive. Moreover, violence of explosion significantly increases decreasing dust size up to an asymptotic diameter (about 30 μm), below which the combustion rate of the dust ceases to increase (Bartknecht, 1989).

The turbulence is always present when a dust explosion occurs: without some degree of fluid motion a dust cloud can not exist because the particles have a tendency to settle out and, as consequence, an explosion wouldn't occur. In standard test vessels an air blast is used to initially suspend the particles, and the turbulence which is generated by the air blast keeps the particles air-borne until ignition occurs. When dust comes into the vessel, the intensity of turbulence is higher and decreases with time. The level of pre-ignition turbulence is

typically measured indirectly by means of the ignition delay time (t_v) which is the time from beginning of dust dispersion at which cloud is ignited. Dahoe et al. (2001) performed measurement of the decay turbulence and found a correlation between level of turbulence (u') and t_v. Turbulence plays a major role in determining explosion characteristics of a dust and is a dominant concern in dust explosion research (Pu et al., 1990; Tamanini and Ural, 1992; van der Wel et al., 1992; Zhen and Leuckel, 1996, 1997). Among the others, Eckhoff (2003) performed explosion tests with lycopodium dust and found increased violence of explosion as the turbulence increases.
Further studies were performed to investigate the characteristics of ignitability and explosibility of dust in the presence of flammable gas or solvent (Cashdollar et al. 1987; Bartknecht, 1989; Amyotte et al., 1993; Chatrathi, 1994). Chatrathi (1994) investigated the ignitability of air-mixture of cornstarch and propane and found that the presence of propane decreases the minimum explosion concentration (MEC) of cornstarch and, similarly, the presence of cornstarch decreases the lower flammable limit of propane. Moreover, at higher concentration of both fuels he observed that the violence of hybrid mixture is higher than that of single fuel in turbulent condition. Bartknecht (1989) studied the explosion of cellulose with adding methane, butane and propane. When gas is added, a consistent increase (higher than 15%) of the deflagration index with respect to that of gas alone was found. In general, the behavior of a hybrid mixture depends on the nature of the specific pair of gas and dust and their relative amount in the mixture (Garcia-Agreda et al., 2011).
The objective of the current work is to review the effects of different parameters by quantifying the role of dust size, ignition source, initial turbulence level, flammable gas admixture on the likelihood and severity of dust explosions.

2. EXPERIMENTAL

The experiments for P_{max}, $(dP/dt)_{max}$, K_{St} and MEC were performed in a 20-L Siwek sphere. The tests were performed in accordance with the ASTM Method E 1226 (2000). The dust particles and compressed air are discharged into the explosion chamber from a pressure canister with a volume 0.4 liter. The explosion chamber is initially evacuated to a pressure of 0.4 bar and the pressure canister is filled with compressed air. The air blast lasts about 50 ms, after which the pressure in the explosion chamber becomes equal to 1 bar and turbulence starts to decay. Some modification were made to perform experiments with hybrid mixtures. Further details regarding the apparatus used and the experimental method followed are reported in a previous work (Garcia-Agreda et al., 2011).
The explosion tests were carried out on nicotinic acid, supplied by Sigma-Aldrich, at different dust concentrations (30-250 g/m^3). Tests were performed using as ignition source either standard chemical igniters of 10000 J or electric spark of lower energy (15 kV, 30 mA). The effect of the turbulence on the behaviour of the explosion was studied varying the value of the ignition delay time (between 30 – 120 ms). Further tests were carried out on hybrid mixtures of methane and nicotinic acid using as ignition source the electric spark. The methane concentration was varied in the range 1-7.3% vol. whereas the concentration of nicotinic acid was varied between 30 to 250 g/m^3. All experiments were carried out in triplicate: the standard deviation and the accuracy of our data are $P_{max} \leq \pm 5\%$ and $K_{St} \leq \pm 20\%$.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results are now presented and briefly discussed for the different parameters investigated.

3.1 Effect of the ignition source

For ignition of a combustible dust-air mixture to result in an explosion, there needs to be an ignition source with adequate initiating energy. The type and strength of the ignition source have a significant effect on the initiation and progress of the explosion.
In Fig. 1 the temporal evolutions of the pressure obtained from explosion of nicotinic acid at C = 125 g/m^3 (left) and C = 500 g/m^3 (right) are shown for two ignition sources: electric spark and chemical igniters.

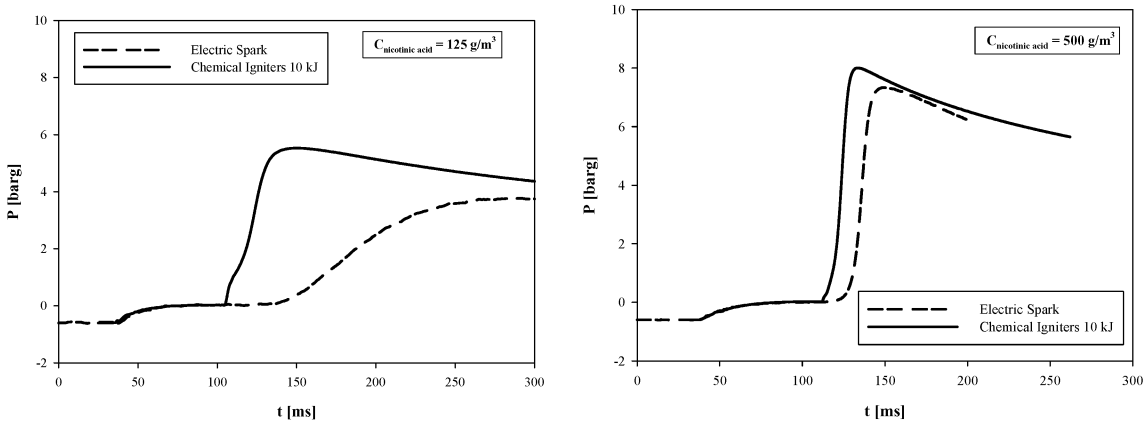

Fig. 1: Comparison of the evolution of the pressure in the time between Chemical Igniters and Electric Spark as Ignition Source for a concentration of nicotinic acid of 125 g/m^3 (left) and 500 g/m^3 (right).

Significant differences in the pressure-time histories are found when the mixture is exposed to the two different ignition sources: the explosion initiated by the volumetric source (chemical igniters) is faster and the rate of pressure rise is higher with respect to the case of the point sources ignition (electric spark). In the case of electric spark ignition, heat is lost near to the point of ignition; then, the reaction takes place at a lower temperature than that of ignition due to chemical igniters, and the reaction rate is much slower; as consequence the overall explosions of the same mixture ignited from the electric spark, are much slower and weaker than those initiated from the chemical igniters (Landman, 1995).

Fig. 2 shows the comparison between the maximum explosion pressure and the deflagration index with respect of concentration of nicotinic acid obtained from tests, either with 10 kJ chemical igniters or electric spark as ignition source. The diagrams have the typical behaviour of dust explosion as pointed out by many cases in literature; moreover, the explosion obtained with chemical igniters as ignition source are more reactive than that obtained with electric spark.

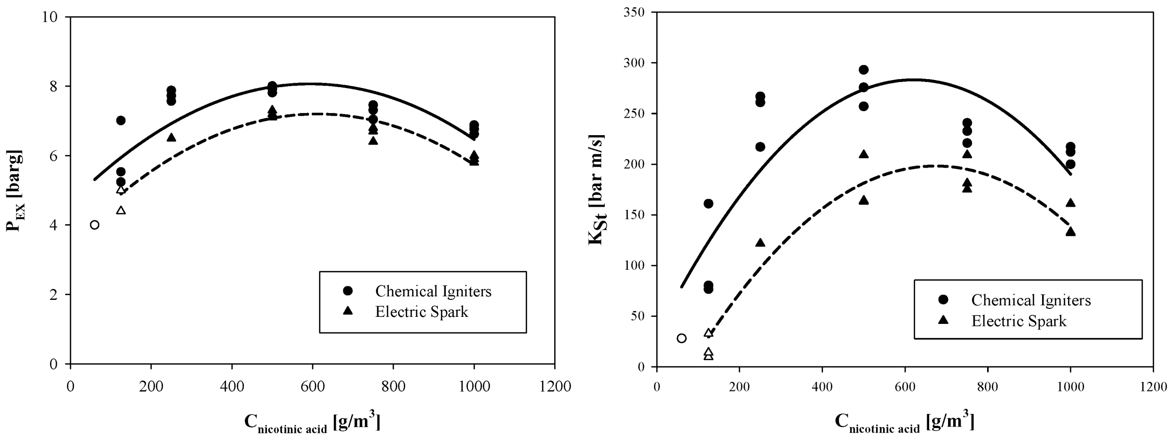

Fig. 2: Maximum explosion pressure (left) and deflagration index (right) vs. nicotinic acid concentration obtained with Chemical Igniters and Electric Spark as ignition source.

In fact, in the tests performed with 10 kJ chemical igniters the maximum value of K_{St}, which is reached for a concentration of 500 g/m^3, is about 280 bar m/s against the maximum value reached for tests performed with electric spark of about 160 – 200 bar m/s at the same dust concentration. This is substantially due to the different modality of energy supply to the system: in the case of chemical igniters the overall energy is released to the system instantaneously; instead, in the case of electric spark the overall energy is released over a long interval of time.

Moreover, from the Fig. 2 it appears that the use of the different ignition systems (chemical igniters or electric spark) determine different values of the MEC (minimum explosion concentration). In particular, in the presence of electric spark, the nicotinic acid at concentration as low as 60 g/m^3 does not ignite, while at this value of concentration, the explosion occurs with higher ignition source of chemical igniters (10 kJ).

3.2 Effect of turbulence

In dust explosion tests, pre-ignition turbulence is necessary for suspending the dust clouds. In the test equipment, a dust cloud is ignited at a delay time (t_v) from beginning of dust dispersion and, hence, at a given initial level of turbulence.

We studied the effect of pre-ignition turbulence at constant ignition source using electric spark. Pre-ignition turbulence level was changed by changing the ignition delay time (t_v) for nicotinic acid-air mixtures.

In Fig. 3 the pressure time histories for nicotinic acid-air mixtures (dust concentration of 500 g/m^3) at different values of the ignition delay time (t_v = 0, 30, 60 and 120 ms) using electric spark as ignition source are shown. On increasing the ignition delay time the maximum pressure and the slope of pressure time curve decreases. This behaviour may be addressed to the decrease of the turbulence level with t_v and also to the particle sedimentation which occurs when the pre-ignition turbulence level is low, due to its temporal decay.

The effect of the turbulence on deflagration index for different concentrations of nicotinic acid is reported in Fig. 4. As the turbulence decreases (higher t_v value), the explosion becomes less violent. In particular, a strong influence of dust concentration on deflagration index is illustrated. This effect can be attributed to changes of the actual dust concentration under the transient turbulent conditions: due to dust sedimentation, the actual dust concentration will become smaller with decreasing turbulence (increasing ignition delay time). This effect is more evident for concentration higher than the stoichiometric concentration (equal to 168 g/m^3 for nicotinic acid), than for lean concentration.

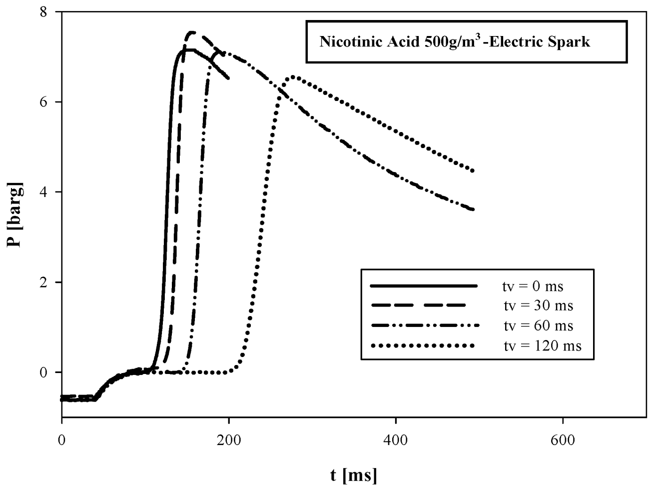

Fig. 3: Evolution of the pressure in time at different ignition delay time using Electric spark as ignition source. Nicotinic acid concentration= 500g/m^3

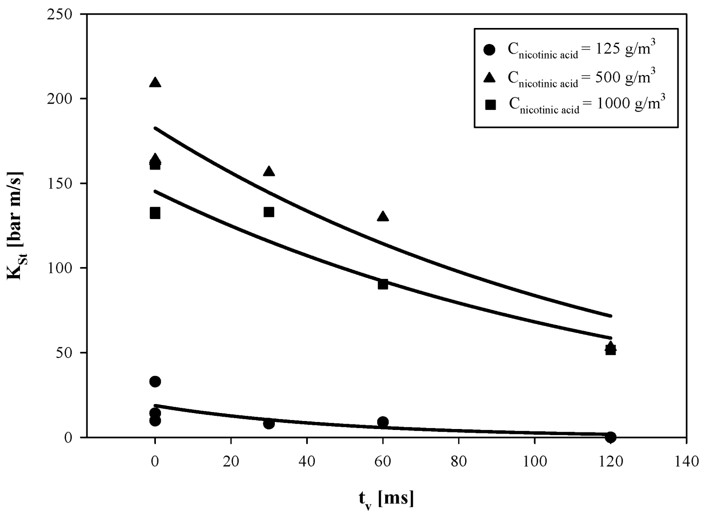

Fig. 4:Deflagration index as function of ignition delay time at different concentration of nicotinic acid (125 – 500 – 1000 g/m^3).

3.1 Effect of gas admixture

The effect of methane gas on the explosion of nicotinic acid was investigated by adding methane, in the range 1.6 -7.3vol %, to the nicotinic-acid air mixtures at different dust concentration.

In Fig. 5 the maximum pressure is plotted vs. the nicotinic acid concentration varying the methane concentration. For dust concentration lower than minimum explosion concentration (MEC = 125 g/m^3) ignition is observed when methane concentration is higher than 3.6 % vol., even if both the fuels are below their flammability (or explosibility) limits.

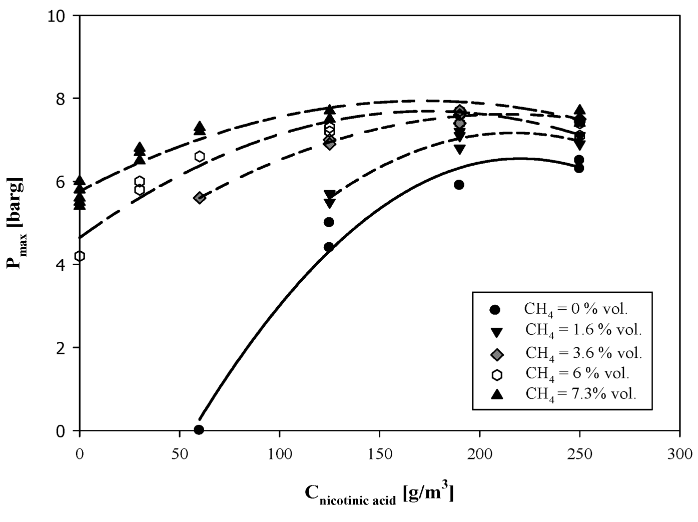

Fig. 5: Maximum pressure as a function of the nicotinic acid concentration at different values of the methane content (Electric Spark, tv = 0).

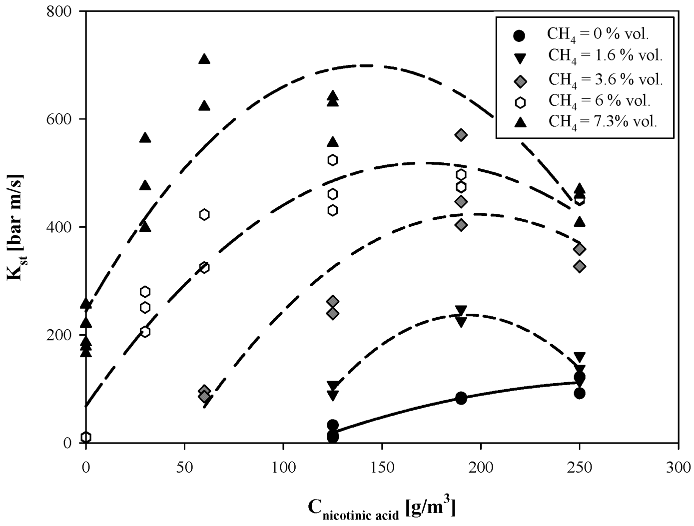

Fig. 6: Deflagration index as a function of the nicotinic acid concentration at different values of the methane content (Electric spark, tv = 0).

In correspondence of nicotinic acid concentrations lower than MEC, the maximum pressure increases as the methane concentration increases; at MEC = 125 g/m^3, the maximum pressure is slightly dependent on the methane content, while at higher values of dust concentration (190 – 250 g/m^3) the maximum pressure seems to be almost independent on the methane content.

In Fig. 6 the deflagration index is plotted vs. the nicotinic acid concentration varying the methane concentration. The nicotinic acid alone unable to ignite at dust concentration of 60 g/m^3, below the MEC, in the presence of methane (3.6 % vol) explodes with a deflagration index of about 96 bar m / s. Significant influence of methane admixture on the deflagration index were observed also at dust concentration equal to the MEC (C = 125 g/m^3), i.e. the deflagration index increases (from 20 to 470 bar m/s) about 20 times when increasing the methane content from zero up to the LFL (6 % vol). This effect is less significant at dust concentration higher than the MEC value and decreases as the concentration of dust increases, i.e. at 190 g/m^{3}the deflagration index goes from 80 bar m/s for dust alone up to 490 bar m / s with 6 % vol of methane in the mixture.

From these results it can be concluded that in the range of concentrations investigated, the admixture of methane to nicotinic acid-air mixtures makes the dust more violent and reactive than the pure nicotinic acid.

Moreover, it is possible to have explosive mixtures at concentrations of methane and nicotinic acid below their lower explosion limits. A possible explanation could be that nicotinic acid is an organic volatile dust and the reaction happens effectively in an homogeneous phase. The devolatilized substance of the dust mixes together with methane gas contributing to enhance the combustible fuel whose mixture has a concentration that falls in the range of flammability.

4. MODEL

A dust explosion is a complex phenomenon in the sense that it involves simultaneous momentum, energy, and mass transport in a reactive multi-phase system. In order to model the dust explosion phenomenon, a precise understanding of the dust explosion mechanism is required. In the case of organic dust producing volatile substances, the explosion occurs in three steps which follow each other in very quick succession (Eckhoff, 2003): i) pyrolysis/devolatilization; ii) gas phase mixing of fuel (released by dusts) and oxidant (usually air); iii) gas phase combustion. The various steps (i.e. heating and devolatilization, heterogeneous combustion) are strongly influenced by the particle diameter. Decreasing the particle diameter they may become extremely fast

with respect to the homogeneous combustion. This happens up to a critical diameter (Peukert, 1996), below which dust explosion does not depend anymore on the dust diameter, but it is mainly controlled by homogeneous combustion rather than by heating, heterogeneous combustion and devolatilization.
We developed a model based on the assumption that the homogeneous reaction kinetic is the controlling step of dust explosion while the other steps are significantly faster (Di Benedetto and Russo, 2007). Hence, the thermokinetic parameters (P_{max} and K_{St}) obtained from the model correspond to the maximum value which is characteristic of each dust and that can be reached when the dust with a diameter lower than the critical value explodes. This value was then adjusted to account for the effect of particle diameter by considering the other steps that may be involved in the explosion of a dust, namely external and internal particle heating, pyrolysis/devolatilization reaction, and volatiles combustion. In practice, the K_{St} of a dust at different diameters was obtained by correcting the K_{St} at the particle diameter approaching zero, with the ratio of the volatiles evolution rate at a given dust size to that relevant to a dust diameter equal to zero (Di Benedetto et al., 2010)

4.1 Model Description

Di Benedetto and Russo (2007; 2010) developed a model for simulating the dust explosion thermokinetic parameters including the effect of the dust size.
The model consists on 3 modules. The first module is the model of simulation of the flame propagation to evaluate the laminar burning velocity, S_l. The second allows the evaluation of the adiabatic pressure (P_{max}), the third consists on the evaluation of the maximum pressure rise (dP/dt_{max}) and deflagration index (K_{St}).
The homogeneous combustion of the gas volatiles was simulated by using a detailed reaction mechanism, the GRI-Mech3.4. This mechanism was implemented in the CHEMKIN module to calculate the laminar burning velocity as a function of the dust concentration. The deflagration index (K_{St}) was calculated by the cubic law here reported:

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

where the maximum pressure rise is calculated according to the formula proposed by Dahoe and de Goey (2003):

$$\left(\frac{dP}{dt}\right)_{max} = \frac{3(P_{max} - P_o)}{R_{vessel}}\left[1 - \left(\frac{P_o}{P}\right)^{\frac{1}{\gamma}} \frac{P_{max} - P}{P_{max} - P_o}\right]^{2/3} \left(\frac{P}{P_o}\right)^{\frac{1}{\gamma}} S_l \tag{2}$$

where P_{max} is the maximum pressure reached in a closed vessel which has been calculated by using the equilibrium module of the CHEMKIN code. S_l is the laminar burning velocity calculated by means of the CHEMKIN module which simulates the laminar flame propagation. R_{vessel} is the radius of the reference spherical vessel (20 l) and Po is the initial pressure (assumed equal to 1 bar).
The deflagration index, maximum pressure and burning velocity calculated are valid for very low values of the dust size and then can be considered as asymptotic values.
In order to quantify the effect of particle size on dust reactivity in an explosion phenomenon, the model takes into account all of the steps involved in a dust explosion: internal and external heating, devolatilization reaction and volatiles combustion. Indeed, varying the dust size it can establish different regimes depending on the values of the characteristic time of each step and of several dimensionless numbers (Damkohler number, Da; Biot number, Bi; thermal Thiele number, Th). In the different regimes, the model is able to calculate the parameter $\chi(d)$ defined as the ratio between the maximum volatiles production rate at a given dust diameter and the maximum volatiles production rate at dust diameter approaching to zero. It follows that once the asymptotic value of the deflagration index ($K°_{St}$) is known, the effect of particle size on the deflagration index can be evaluated according to the pyrolysis model by the following equation:

$$K_{St}(d) = K_{St}^{o} \cdot \chi(d) \quad (3)$$

4.2 Model results

The capability of the model to predict the maximum value of deflagration index for dust particles of different size is shown in Fig.7. In the Fig.7 experimental K_{St} for dust samples of polyethylene of different sizes in the range 28-916 μm is reported as function of particle volume median diameter D(v,0.5) (Amyotte et al., 2008). The data are relevant to different concentrations of dust of a given particle size. The rate at which pressure development occurs is strongly influenced by a reduction in particle size: K_{St} increased significantly by a decrease in particle size.

In the same figure the model line is shown as determined using the thermo-kinetic model previously reported by Di Benedetto and Russo (2007, 2010) taking into account the effect of particle diameter on the dust heating and volatilization processes. Good agreement is shown in Fig.7 between the dust experimental and model results: the model is able to predict the maximum value of deflagration index for particle size in all the range investigated.

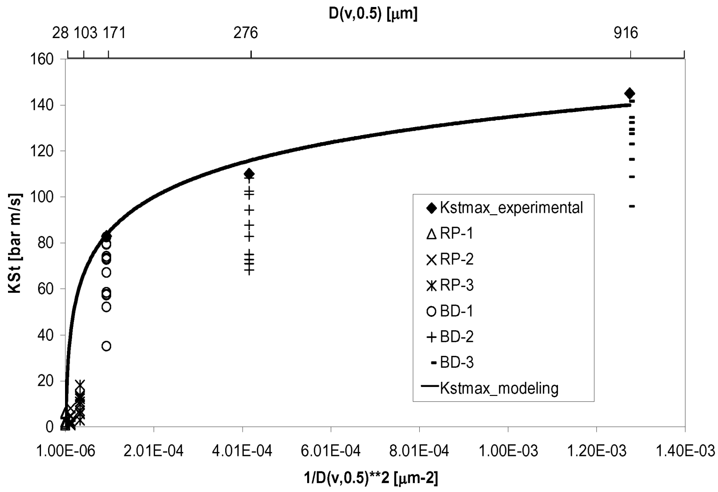

Fig. 7: Modelling results for polyethylene at different size fractions.

5. CONCLUSIONS

The current study has attempted to quantify the effects of ignition source, pre-ignition turbulence level, particle size reduction and flammable gas admixture for severity of dust explosion. Fine particle sizes of dust and admixture of flammable gas to a combustible dust were observed to enhance the explosion hazard with respect to several explosibility parameters: maximum explosion pressure, maximum rate of pressure rise, size-normalized maximum rate of pressure rise, minimum explosible concentration. The effect of turbulence on deflagration index is minor in standard test conditions, while it is significant at high initial turbulence level. The effect of the ignition energy was studied using different ignition source, electric spark and chemical igniters. In the case of strong igniters the effect on explosion process can be comparable to that of turbulence.

The thermo-kinetic model here shown gives a good prediction of the deflagration index at varying the dust diameter.

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