# INFLUENCE OF CONCENTRATION AND PARTICLE SIZE ON THE EXPLOSIBILITY OF AIR PINE BARK DUST MIXTURES

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**Abstract.** *Studies on the explosibility and ignition characteristics of air and pine bark dust mixtures were carried out in a semi-spherical 22.7 L reactor using 2500 J pyrotechnic ignitors. The uniformity of the dispersion of the pine bark dust particles inside the chamber was detected through optical probes and during the explosion the pressure evolution inside the reactor was measured. Four particle sizes with 51.3 $\mu m$, 88.4 $\mu m$, 104.2 $\mu m$ and 180.2 $\mu m$ of mass median diameters were tested and the covered dust cloud concentration went from 60 $g/m^3$ to 600 $g/m^3$. Measured explosions parameters included minimum explosible concentration, maximum explosion pressure and maximum rate of pressure rise.*
*The effect of dust particle size on the explosibility was evaluated and it was found that minimum explosible concentration was relatively independent of particle size below 100 $\mu m$. The highest explosion pressures and rates of pressure rise were detected for the finest tested sizes.*
*The limitations on the devolatilization rate of the solid particles are the rate controlling phenomena at high dust loadings and large particle sizes.*

*Keywords. Dust explosion, explosion development, two-step dust explosion, pine bark*

## 1. Introduction

Process industries which have in some steps of their production cycles the presence of dusts are risky institutions as far as fire and explosion hazardous are concerned. As such, the knowledge of the menace of the materials involved in the production cycle is fundamental for the industrial safety of the plants. One industrial sector highly dependent on the handling of organic dusts is the wood and wood derivatives segment.

An explosion can be defined as propagation, in a closed vessel, of a flame in a pre mixture of suspended dust in a gaseous oxidant such as air. During the explosion there is a rapid and abrupt energy release which produces a pressure wave. The resulting rapid oxidation of the fuel dust leads to a rapid increase of the overall temperature and pressure. The combustion properties of a dust depend on its chemical and physical characteristics, especially on the particle size distribution (Eckhoff, 1997).

For a two phase mixture of dust in air, the perfect mixture is impossible, and at least one additional variable is required in order to define composition on the macroscopic scale, which determines its combustion behavior. That additional variable is the particle diameter. In other words, a given amount of solid material, suspended in air inside a container presents no explosion hazard; however, the same amount when pulverized into a fine dust of less than 100 μm in diameter and uniformly dispersed in air, inside that same volume, may become an explosive mixture. The thermodynamic states of those two systems are essentially identical, but their dynamic behavior is vastly different. Thus, the state of the heterogeneous system is not uniquely defined by its macroscopic composition, temperature and pressure; the particle diameter is critical in defining the fuel concentration on the microscopic scale that determines its dynamic combustion behavior (Hertzberg et al., 1986).

This paper concerns a small part of the study and definition of explosion characteristics of air pine bark dust mixtures and is oriented towards the analysis of the influence of particle median diameter on the minimum explosible concentration, on the maximum explosion pressure and on the maximum rate of pressure rise, for dust explosions at initial normal pressure and temperature.

The chemical composition of pine bark (Pinus pinaster) was investigated by Fradinho et al. (2002). Pine bark is being composed mainly by lignin (33.2%), tannins (10 % w/w), polysaccharides (39 % w/w), formed essentially by cellulose and hemicellulose, 17 % (w/w) of other components (like ethanol, water and dichloromethane) and 1% (w/w) of ashes.

## 2. Experimental set-up

Pine bark dust explosibility results discussed in this paper were obtained in a near-spherical 22.7 L test chamber, as shown in Fig. (1). This chamber is made of stainless steel and is a standard laboratory test chamber (ASTM E1515; ASTM E1226), used extensively for dust explosions studies of carbonaceous and elemental dusts (Hertzberg et al., 1986; Cashdollar et al., 1988 and Cashdollar, 1994). Its dimensional characteristics were provided by the Pittsburg Research Laboratory formerly part of the US Bureau of Mines (USBM) and now at the National Institute for Occupational Safety and Health (NIOSH).
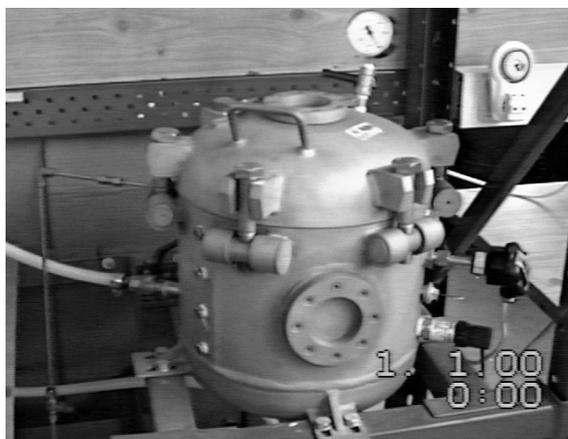


Figure 1. Semi-spherical test chamber of 22.7 L.

One optical dust probe (Conti et al., 1982 and Cashdollar et al., 1981) was used to evaluate the uniformity of the dust dispersion by measuring the light transmission over a 38 mm path length through the dust cloud.

The evolution of the explosion pressure and rate of pressure rise during the explosion was measured with a pressure transducer with internal diaphragm for absolute pressures in the range of 0-10 bar, make IMT, model 3245, with an accuracy of 0.5 % (F.S.), reproducibility $\leq \pm$ 0.05% (F.S.) and a response time $\leq$ 1 ms (within 10 to 90 % of F.S.).

The data acquisition system was composed by a personal computer of 66 MHz inside of which it was installed a data acquisition board from Keithley-Metrabyte, model DAS-1601. The experimental dust concentration reported for the chamber is the mass of dust divided by the chamber volume.

## 3. Experimental procedure

After the dust batch and the ignition device have been placed in the chamber, the top lid is bolted on and the chamber is partially evacuated to an absolute pressure of 0.20 bar. Then, a short blast of dry air from a 16 L auxiliary dispersing tank with 0.3 seconds duration disperses the dust and raises the chamber pressure to about 1 bar. The ignitor, located in the centre of the reactor, is activated after an additional delay of 0.1 s resulting in a total ignition delay of 0.4 s, from the start of dispersion until ignition, as suggested by the standard test procedure (ASTM E1515; ASTM E1226). The ignition sources used were electrically activated pyrotechnic ignitors composed of 40% (w/w) zirconium, 30% (w/w) barium nitrate and 30% (w/w) barium peroxide and were supplied by Fr. Sobbe, from Germany. They deliver their energy in about 10 ms and when ignited they produce a dense cloud of very hot particles and little gas (Hertzberg et al., 1986a). The 2500 J ignitors by themselves produce a pressure rise of about 0.27 bar in the chamber, as verified in calibration and set up experiments (Pilão, 2002; Pilão et al. 2002a, 2002b, 2004, 2006).

## 4. Results

In order to study the overall explosibility characteristics of pine bark dust, tests were made over a range of concentrations that went up to 800 g/m³ for four different particle diameters. Experiments were carried out with pine bark particles of 51.3 μm, 88.4 μm, 104.2 μm e 180.2 μm particle diameters. Particles were screened with ASTM sieves and the particle sizes referred above are the mass median diameters obtained through LASER dispersion. From these tests, traces representing the evolution of explosion pressure as function of time are obtained.

### 4.1. Explosion development

The configuration of the traces of explosion pressure as function of time have shown that pine bark has a normal development of the explosion, with a typical profile of pressure time trace for near spherical flame propagation (Amyotte et al., 1989 and Hertzberg et al., 1987), only for the two smallest particle sizes (51.3 μm and 88.4 μm), while

a two-step flame propagation process, in the explosion development, was detected for the particles with 180.2 μm of diameter. The transition between these two explosion processes occurred for the particles with 104.2 μm.

Figure (2) has examples of the evolutions of explosion pressure and rate of pressure rise during the explosion of clouds with particle diameters of 51.3 μm. The explosion pressure increases quickly with the explosion time and higher values are obtained for higher loaded dust concentration. The violence of the explosion, increase with the dust concentration. In this figure, the first 15 ms are concerned with the activation of the ignition source and the creation of an initial fire sphere, whose volume is dependent upon the energy of the ignition source used. This fire ball generates heat and assures the initial flame propagation. Then, the flame speed increases resulting in the rapid increase of pressure inside the reactor. The inhomogeneities in the concentration and dust particles distribution inside the reactor inevitably generate noncontiguous flame fronts, and propagation occurs in streaky filaments or patches of flame that follow those regions that have slightly higher dust concentrations (Hertzberg, 1986).

The results of the explosions obtained during the tests carried out with particles of 104.2 μm do not have a systematic behavior. For some tests, carried out with concentrations near the lower flammability limit, an explosion development in two phases was observed. This two-step flame propagation process is characterized by the appearance of two ramps on the explosion pressure curve and two peaks in the rate of pressure rise curve, Fig. (3). The first step of this process, represented by the first pressure rise after ignition, is associated with small initial burning velocities and with the upward and horizontal direction of flame propagation, while the second step, represented by the subsequent pressure rise, is associated with downward flame propagation at a fast burning velocity (Linnett and Simpson., 1957 and Cashdollar et al., 2000). In Figure (3), results of explosions for clouds of particles of this size with dust concentration of 200 g/m$^3$ and 700 g/m$^3$ are presented. The explosion development carried out with suspension of 200 g/m$^3$ follows a two-step flame propagation process. In this test, the first 100 ms are concerned with the first phase of the process characterized by the first smooth pressure increase and the first peak in the rate of pressure raise trace. The second phase of the process was initially developed at constant rate of pressure rise after which there is a further increase on the flame speed causing a second rise of the explosion pressure and the appearance of the second peak in the trace of the rate of pressure rise. This flame speed acceleration results from the compressing effect promoted by the burned gases from the first phase of the process (Cashdollar et al., 2000). This two-step behavior for the flame propagation process has the tendency to disappear with the rise of dust concentration. For the test with 700 g/m$^3$ no clear transition in the flame direction propagation, between ascending and descending displacement , was detected, as can be observed in Fig. (3).

In Figure (4) there are examples of results obtained for the particles with 180.2 μm. The explosion development follows a two-step flame propagation process, for all tested dust concentrations. The traces of explosion pressure have two distinct zones of pressure increase and the traces of rate of pressure rise have two peaks with the second phase of the process characterized by higher flame propagation speeds, associated to the descending flame propagation.
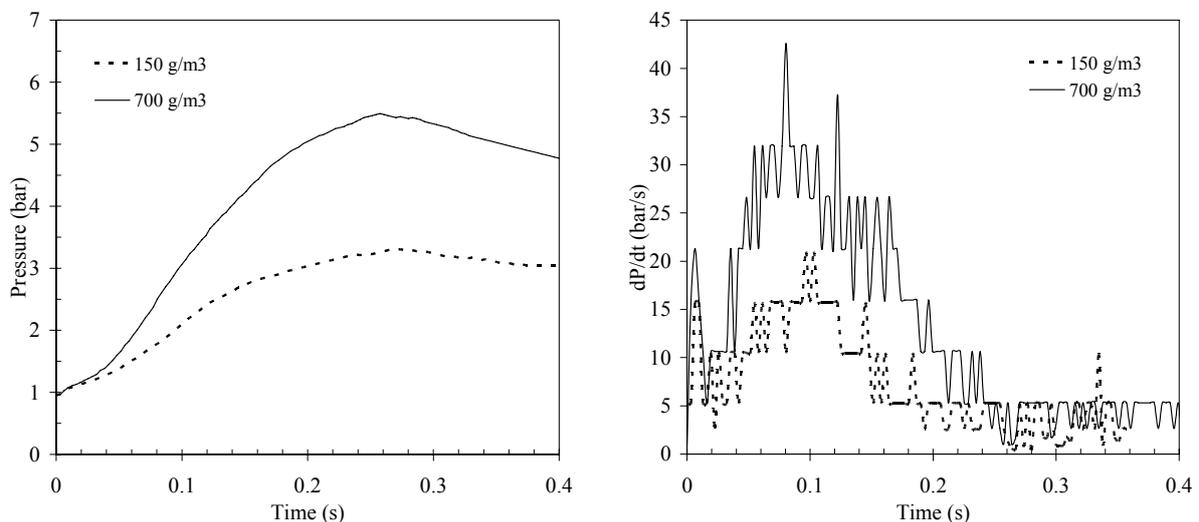


Figure 2. Effect of dust concentration, on the explosibility of bark dust particles, with 51.3 μm of mass median diameter.
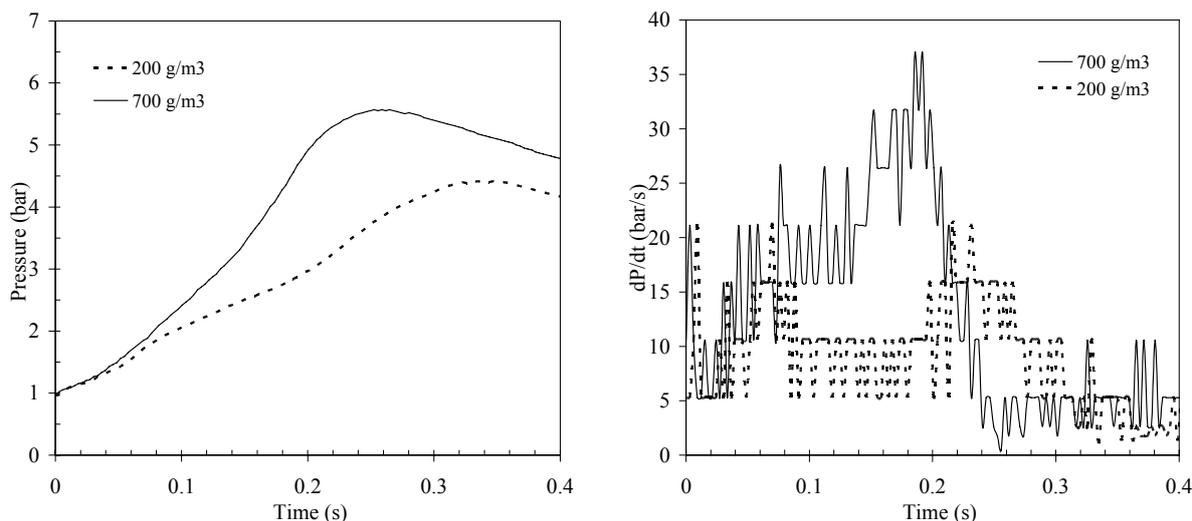
Figure 3. Effect of dust concentration, on the explosibility of bark dust particles, with 104.2 μm of mass median diameter.
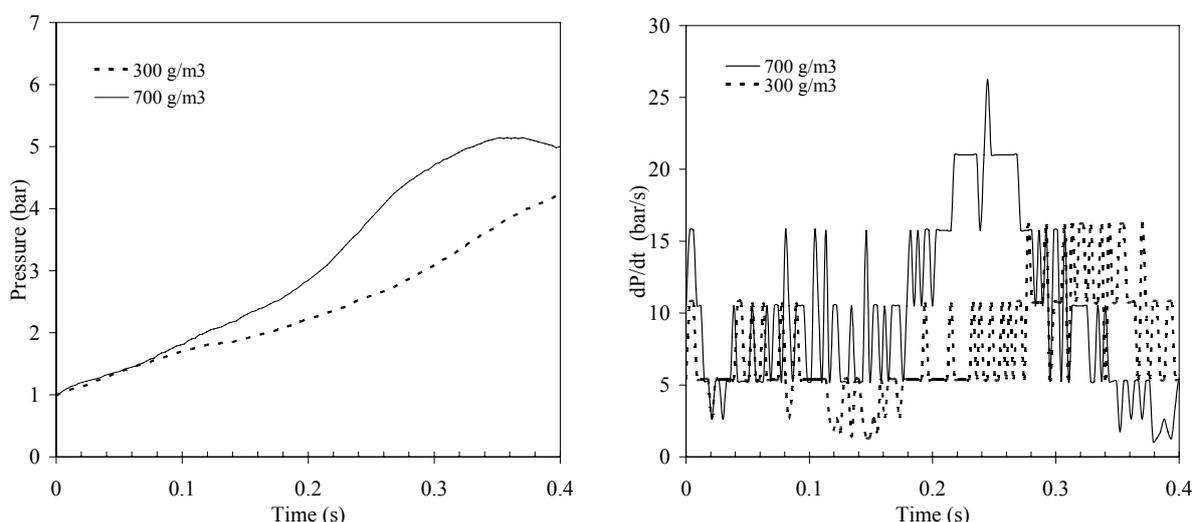


Figure 4. Effect of dust concentration, on the explosibility of bark dust particles, with 180.2 μm of mass median diameter.

### 4. 2. Explosion parameters

The study of the explosibility of pine bark dust/air mixtures comprises the experimental determination of the minimum explosible dust concentration, the maximum explosion pressure and the maximum rate of pressure rise.

From the traces representing the evolution of explosion pressure as function of time, obtained during the experimental tests, the pressure ratio PR and the steepest slope of the rising portion of the curves (dP/dt) can be both represented as function of concentrations, for each one of the studied particle sizes.

PR is defined as $PR = \left(P_{max} - \Delta P_{ign}\right)/P_i$ where $\Delta P_{ign}$ is the pressure rise promoted by the activation of the ignition source, $P_i$ is the initial pressure in the reactor and $P_{max}$ is the peak of the traces.

The criteria for significant flame propagation were the same as used previously at USBM (Hertzberg et al., 1986b; Cashdollar et al., 1992 and ASTM E1515). These criteria are that the maximum explosion pressure PR≥2 bar and that the volume normalized rate of pressure rise (dP/dt)V1/3 ≥1.5 bar.m/s. Applying these criteria to the obtained results, the minimum explosible dust concentration can be determined for each one of the tested particle sizes. Maximum values of explosion pressure PR and rate of pressure rise dP/dt are also obtained from these traces.

Data showing the effect of particle size on the minimum explosible concentration, $C_{min}$, of pine bark are shown in Fig. (5), together, with the information concerning cork dust and Pittsburg coal dust.

Figure (5) shows that for fine particles of pine bark, with mass median diameters smaller than 100 μm, the minimum explosible dust concentration is relatively independent of particle size assuming the value of 90 g/m³. Above this diameter, defined as the characteristic diameter, the size dependence appears.

According to the flame propagation mechanism proposed by Hertzberg et al. (1982) and Hertzberg et al. (1990), the flame propagation is a sequential process starting by the devolatilization of the particles followed by the mixture of the emitted volatiles with the air, and finally by the combustion, in the gaseous phase, of the resultant air combustible mixture. This theory stated that the reaction time of an explosion is composed by two essential components: the devolatilization time of the particles and the combustion time. The time of devolatilization depends on the particle size, while the combustion time is independent of the dimension of the particles, because the combustion process is a gaseous phase phenomenon. This means that, a process controlled by the reaction rate is independent of the size of the particles, while a process controlled by the devolatilization rate is dependent on the dimensions of the particles. The flat region of the curves in Fig. (5) means that, for particles with sizes smaller than the characteristic diameter, the explosion process is controlled by the chemical reaction rate. However, in the case of pine bark dust, this flat region does not correspond to situations of complete devolatilization of the particles within the flame front, as is commonly admitted for dust of small sizes, (Hertzberg *et al.* 1986b). In fact, it was observed that a significant amount of particles remains unburned in the final of the explosion tests, which can be confirmed by the evolution of the burning efficiency, defined as $\eta = (m_i - m_f)/m_i$ . In the previous definition $m_i$ and $m_f$ are the initial and the final mass of pine bark dust batch. The results have shown that the combustion efficiency increases with the rise of the dust concentration until it attains the maximum value of 67 %. The stabilization of this value is related with the oxygen content inside the reactor, which imposes the maximum burnable volatile content.
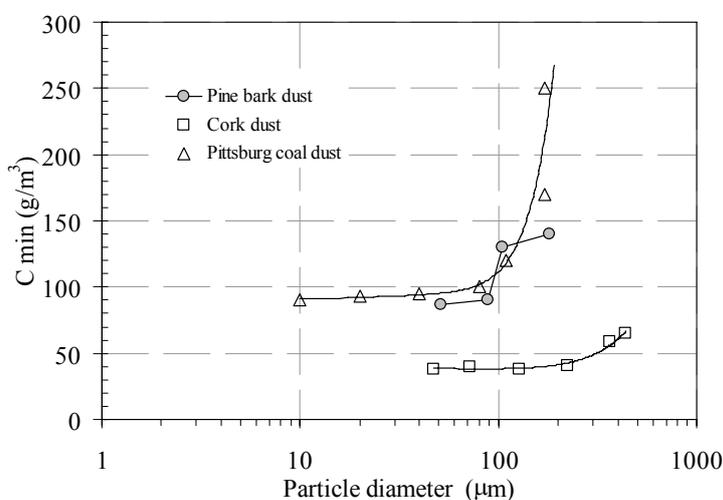


Figure 5. Effect of particle median diameter on minimum explosion concentration of pine bark dust air mixtures.

In conclusion, the flat region of the curve obtained for pine bark dust in Fig. (5) represents situations where the quantity of the volatiles generated is independent of the dimension of the particles and the explosion occurs, if in gaseous phase it will be present a minimum necessary volatile content. For larger particles, only the particle surface is de-volatilized and consequently a higher mass of dust must be loaded to reach, in the gaseous phase, the minimum dust concentration.

The devolatilization of the particles can be confirmed by their observation before and after explosion. Figure (6) shows scanning electron microscope (SEM) photomicrographs of pine bark dust particles with 88.4 μm mass median diameter before and after explosions of a dust cloud with a concentration of 400 g/m³. This figure shows the morphological changes resulting from dust explosions, and it is clear that the structure of the surface of the residues is strongly altered, when compared to the unburned particle. Some particles form cenospheres, and the volatiles are emitted through the holes seen in the residues. These photomicrographs provide evidence that the pyrolysis process proceeds like a devolatilization wave front that is initiated at the exposed surface and then propagates towards the particle interior. This behavior confirms that the flame propagation process during the pine bark dust explosion is preceded by the devolatilization of the particles (Hertzberg et al., 1982 and Hertzberg et al., 1990).

In Figure (7) maximum explosion pressure and maximum rate of pressure rise, as a function of the pine bark dust particle size, are presented. The two curves show that the maximum pressure and rate of pressure rise are found at the smallest tested size and have the maximum values of 5.5 bar and 42 bar/s respectively. Then, with increasing particle size, the pressure values decline slowly, whereas the decrease of the rate of pressure raise is stronger.
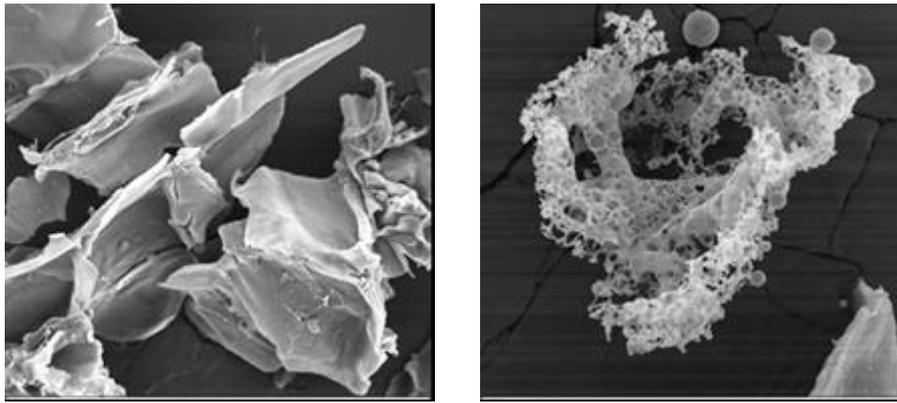
Figure 6. Scanning electron microscope (SEM) photomicrographs of pine bark dust particles of 88.4 μm diameters before and after explosions for a dust cloud concentration of 400 g/m$^3$.

The evolution of the maximum explosion pressure curve with the increase of particle diameter is an indication that there are not significant changes in the volatile concentration of gas phase. At elevated concentrations, at which are obtained the maximum explosion pressure and the maximum rate of pressure rise, the burning velocity is high but the depth of penetration of the combustion wave, which varies inversely with the burning velocity $S_u$, decreases and becomes less than the average particle radius (Cashdollar et al., 1988 and Smoot et al., 1976). The excess undevolatilized mass fraction of pine bark plus the residual char, at the higher dust loadings, makes no contribution to the flame propagation process; it begins to absorb a large fraction of the heating flux of the flames (Hertzberg et al., 1982) and the effective heating flux, that drives the fresh pyrolysis wave ahead of the flame front, is diminished. As the particle diameter increases still further, the pyrolysis wave progresses more slowly into each particle, and this effect is accentuated with the increase of particle diameter. As a result, there is a smaller contribution of volatile from each particle that is compensated for by the higher surface area of the particles.
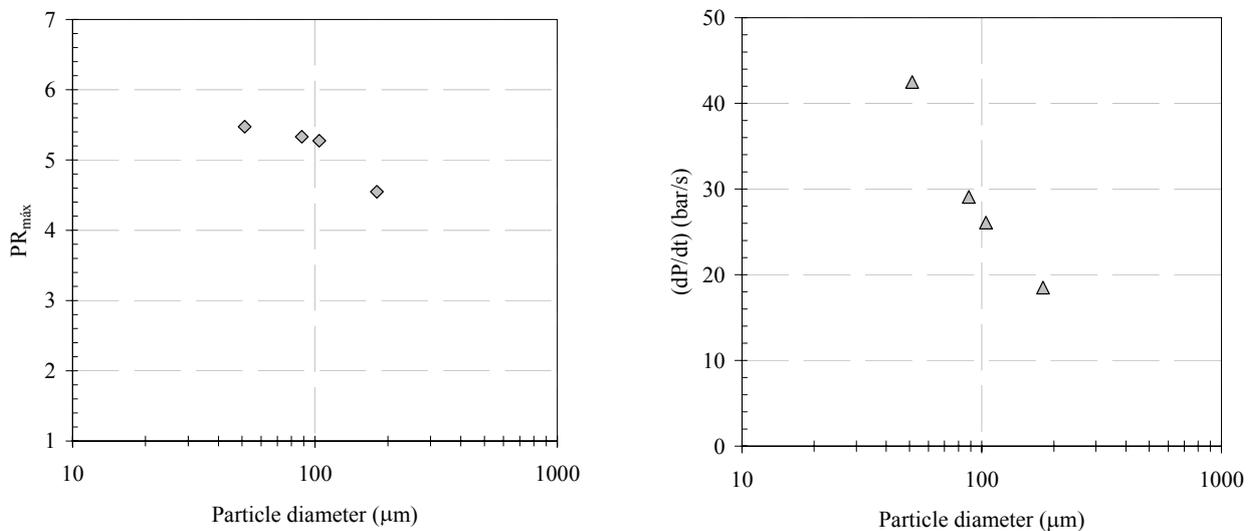


Figure 7. Effect of particle diameter on maximum explosion pressure and maximum rate of pressure rise, for pine bark dust air mixtures.

The strong dependency of the maximum rate of pressure rise relatively to the particle diameter is caused by the accentuated diminution on the velocity of the devolatilization process, when the particle diameter increases. The burning velocity $S_u$ is strongly dependent on the rate of volatiles generation and decreases with the reduction of the progression of the devolatilization wave through the particles. As the maximum rate of pressure rise is proportional to $S_u$, dP/dt diminishes drastically with the increase of the particle diameter, as is shown by several models (Bartknecht, 1981 and Nagy and Verakis, 1983).

**5. Conclusions**

 Particle size and dust concentration have an important effect on the explosibility behavior of pine bark dust.

 Small particles of pine bark dust follow a near spherical flame propagation while larger particles follow a two-step flame propagation process.

The results obtained show that finest particles produce more violent explosions than the larger ones, and the evolution of the explosion parameters with the particle diameter show that the explosion pressure is essential a thermodynamic component, while the maximum rate of pressure rise has a strong kinetic component.

The explosion of pine bark dust follows the propagation flame mechanism proposed by Cashdollar and Hertzberg. In these theories, the flame propagation in the gaseous phase combustion is preceded by the devolatilization process of the dust particles. For the smaller particles, the combustion process is controlled by the combustion velocity, whereas for the bigger particles, the combustion process is controlled by the devolatilization rate.

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