FORMATION OF EXPLOSIBLE COAL DUST CLOUDS

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ABSTRACT

The research investigates about the hazard of formation of explosible coal dust clouds inside thermoelectric plants. The study was addressed to experimentally measure two key-parameters for risk analyses: the potential resuspension rate of dust layers and the minimum explosible concentration of the clouds that can be generated. Representative samples of coal dust were collected from components and floors of typical power plants and characterized in terms of density, burnable fraction, morphology and size distribution. A small-scale experimental facility was set-up to perform ad-hoc tests to quantify the fraction that can be resuspended in airborne form due to an air jet. In this apparatus, the samples were subjected to fully turbulent gas flows, with velocities ranging from 0 to more than 50 m/s. Over 80 experimental tests were carried out, obtaining good repeatability and continuity of the results. A high speed video camera was also used to observe the fluid-particle interaction and the behaviour of the particle entrainment inside the bulk flow. The analysis of the results indicated that the mobilization of coal dust is detectable at air speed higher than 6-7 m/s. The experiments clearly showed that the mixing of air and particles is not instantaneous, as the dust particles roll and jump before being injected into the gas bulk. This behaviour can create a flow zone, situated near the surface of dust deposits, having a wide range of particle concentration, that can fall within the explosibility range. As regards the explosibility, the attention was focused on an experimental campaign devoted to measure the Minimum Explosible Concentration of the same coal dusts, as a function of the most relevant factors (i.e. size distribution, moisture content, initial temperature). For the collected coal dusts, the measurements gave a Minimum Explosible Concentration ranging from 40 g/m^3 to 70 g/m^3, with some influence of particle size and moisture content.

1.0 INTRODUCTION

If a deposit of dust is subjected to a turbulent gas flow, the aerodynamic forces can prevail the adhesive ones and promote the lifting of particles: the entrainment of particles into the gas flow is known as “aerosol physical resuspension”. The removal of large particles, not necessarily lifted out of the gas boundary layer, is often defined with the term “dust mobilization”. This phenomenon has an important role in the release of radiotoxic substances from nuclear and chemical installations in case of accident and, if the dust particles are flamable, it can be responsible for the formation of explosible clouds. This latter problem, in particular, is known since flour mills had to be widely employed.

Today, the resuspension of flamable dust has significant importance in all industrial plants where burnable solid compounds are treated, as natural organic materials (grain, linen, sugar, etc.), synthetic organic materials (plastics, organic pigments, pesticides, etc.), coal or metals (e.g. aluminum, zinc). In the field of electric power generation, the risk of explosible cloud formations is related to the transport and milling of coal inside the power plants.

In Italy, as there is a significant interest in pushing the utilization of this fuel, this problem is getting some attention by safety specialists. For this reason, a research study was carried out by CESI in the framework of the “electricity system research”, Project SISET, whose funding has been provided by means of a levy on the electricity bills paid by the customers of the electric service.

The target of this study, then, was the minimization of the hazard of coal dust explosions by providing reference data and simulation tools that can be used for monitoring the risk of explosible concentrations in different steps of the production of thermoelectric energy.

2.0 THE REFERENCE DUST SAMPLES

Several studies were managed in the past years to quantify the resuspension dependence on gas velocity, particles characteristics and size, particularly in the nuclear safety field [1]. In spite of the acquired knowledge and the experimental databases, however, the developed simulation models are not yet widely accepted by the scientific community because they can be applied only to very simple theoretical situations or because they cannot be directly extended to a wide range of materials and types of particles.

In the experimental research presented in this work, the reference dust samples were collected in order to grant the representativity of the different areas influenced by the presence of dust in coal-fired power plants: pneumatic conveyors, mills and other auxiliary structures (Fig. 1). As regards their properties, the dust samples were characterized in terms of density (by means of liquid filling), morphology (SEM) and size distribution (laser diffraction). As expected, the largest particle deposits were found on the horizontal surfaces and the finest ones on structure walls (Tab. 1 and Fig. 2).

Fig. 1 – Typical example of coal dust deposits around a belt conveyor.

Fig. 2 - Image obtained by electron microscope of one of the coal dust samples used in the experimental campaign.

Tab. 1 – Size and actual density of the coal dust deposit samples.

Sample	Geometric mean diameter [μm]	Geometric standard deviation [-]	Actual density [g/cm^3]
1	59.44	2.06	0.915
2	73.60	1.95	1.096
3	55.53	2.00	0.922
4	200.48	3.28	1.043
5	131.77	2.26	1.173
6	56.66	2.58	1.095

3.0 MEASUREMENT OF DUST RESUSPENSION

The resuspension of the coal dust samples was observed and measured in a small-scale experimental facility, set-up at CESI laboratories just for this purpose, and called SOFFIA (Sospensione Ottenuta Facendo Fluire Improvvisamente Azoto, i.e. suspension obtained by suddenly flowing nitrogen). Also, "soffia" means "blow" in Italian. This apparatus was designed to perform ad-hoc tests to quantify the mass that can be resuspended in airborne form because of an air jet. The coal dust samples, having an exposed surface of 3x20 cm, few millimeters thick, were subjected to fully turbulent gas flows, within a plexiglas square duct 5x5 cm-section, 50 cm long.

Representative conditions of plant structures located close to a deflagration point were obtained by generating gas velocities higher than 50 m/s. The velocity regulation was made by discharging a 1000-liter pressure tank into the duct, acting on a damper and charging a the tank at different gas pressure levels. To avoid any ignition of the resuspended coal dust, nitrogen was chosen as carrier instead of air, whilst water sprays were positioned downstream the test section (Figs. 3 and 4).

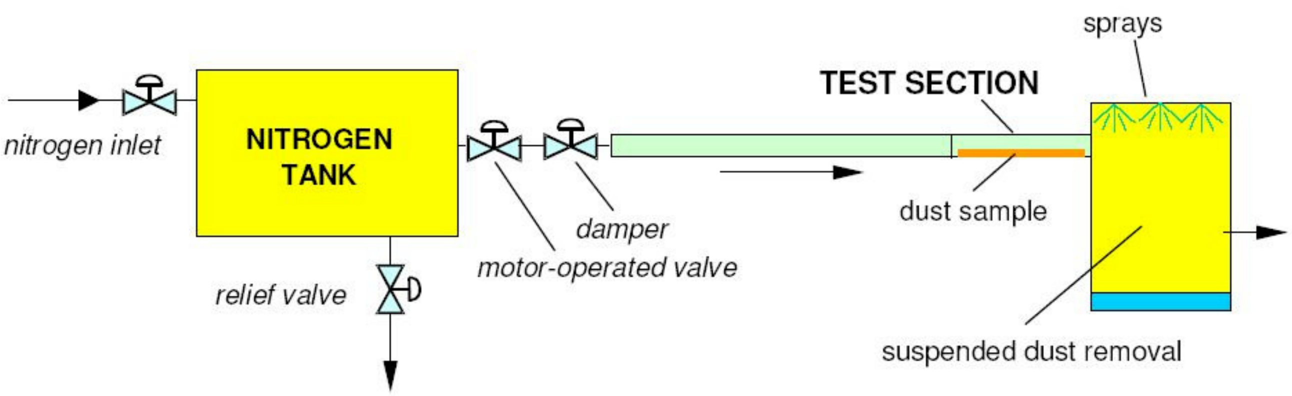

Fig. 3 – Simplified scheme of the experimental apparatus SOFFIA.

Each resuspension test implied the preparation of the dust samples of some millimeters over the plate and the measurement of their initial weight. Each plate was positioned inside the test section of the duct and fixed.

The quantification of the possible resuspension/mobilization of the dust was made by opening the motor-operated valve for a pre-fixed time duration, of the order of few seconds, and then weighting the dust remained on the plate. It was possible to observe the dust resuspension phenomenon through the transparent walls of the plexiglass duct. During each experiment, gas velocity, temperature and pressure were recorded with a computer-controlled system.

Over 80 experimental tests were carried out using the collected coal dust samples, obtaining good repeatability and continuity of the results. In addition, with the aim of making theoretical interpretations and model developments possible, further tests were performed using different materials (graphite, steel, tungsten, glass, zirconia and granite), with significantly differing values of density, shape and size from those of coal dust particles. A high speed video camera was also used to understand the fluid-particle interaction and the behaviour of particle entrainment into the bulk flow.

Fig. 4 – The experimental apparatus SOFFIA, used for measuring the dust resuspension rate.

The phenomenon was then quantified in terms of resuspension rate. This physical quantity represents the fraction of aerosol deposit that is removed per time unit.

Let's consider a sample surface of area A, on which a loading mass M_0 is deposited at the beginning of the observation. If ΔM is the resuspended mass from the surface in the time interval Δt, the resuspension rate Λ can be simply defined as the limit, for $\Delta t \to 0$, of the ratio of the resuspended mass ΔM to the deposited mass M_0 (1). According to [2], as the experiments performed with the facility SOFFIA lasted some seconds, the resuspension rate was evaluated with a logarithmic formulation, that can better approximate the decrease of the deposited mass during the observation time (2):

$$\Lambda = \lim_{t \leftarrow 0} \frac{\Delta M / A}{M_0 / A} \frac{1}{\Delta t} = \frac{1}{M} \frac{dM}{dt} \qquad (1)$$

$$\Lambda = -\frac{\log\left(M / M_0 \right)}{\Delta t} \qquad (2)$$

The overall response obtained by the analysis of those tests is summarized in the graphic of Fig. 5, where the resuspension rates of the six coal dust samples, evaluated by applying the logarithmic formula, are reported as a function of gas velocity. The analysis of the results indicates that the mobilization of dry coal dust is detectable at air gas velocity higher than 6 - 7 m/s.

During the experimental campaign, in order to better understand the resuspension phenomena, some experiments were observed with a high speed video camera. From the analysis of the videos, it was noticed that the resuspension did not involve all the particles of the sample: most of them roll and jump over the sample surface (Fig. 6). Also, a threshold gas velocity was detected: only if the gas reaches this "fluid threshold velocity", as defined by [3], the particles began to move rolling over the other settled particles. The rolling particles gradually gain velocity and, hitting the other particles, begin to jump (this phenomenon is called saltation). These jumps allow the particles to enter the bulk flow and to receive energy from the gas flow. In this way, they can acquire higher velocity than just rolling and, if they fall again on the deposited particles, they can transfer part of their energy to these ones. Only a fraction of the saltating particles can enter the gas bulk flow and can be definitely assumed as dispersed in the gas phase: in other words, there is not a final partition between rolling, jumping and suspended particles, as they form a fluidized bed, through a phenomenon also known as surface creep or reptation [4].

Starting from the sample surface, a decreasing particle number density was observed: this is very important, because near the surface the airborne particle concentration is higher than the minimum explosible concentration.

Further tests were performed using different materials (graphite, steel, tungsten, glass, zirconia and granite), with values of density, shape and size significantly differing from those of coal dust particles, obtaining a confirmation of that behaviour.

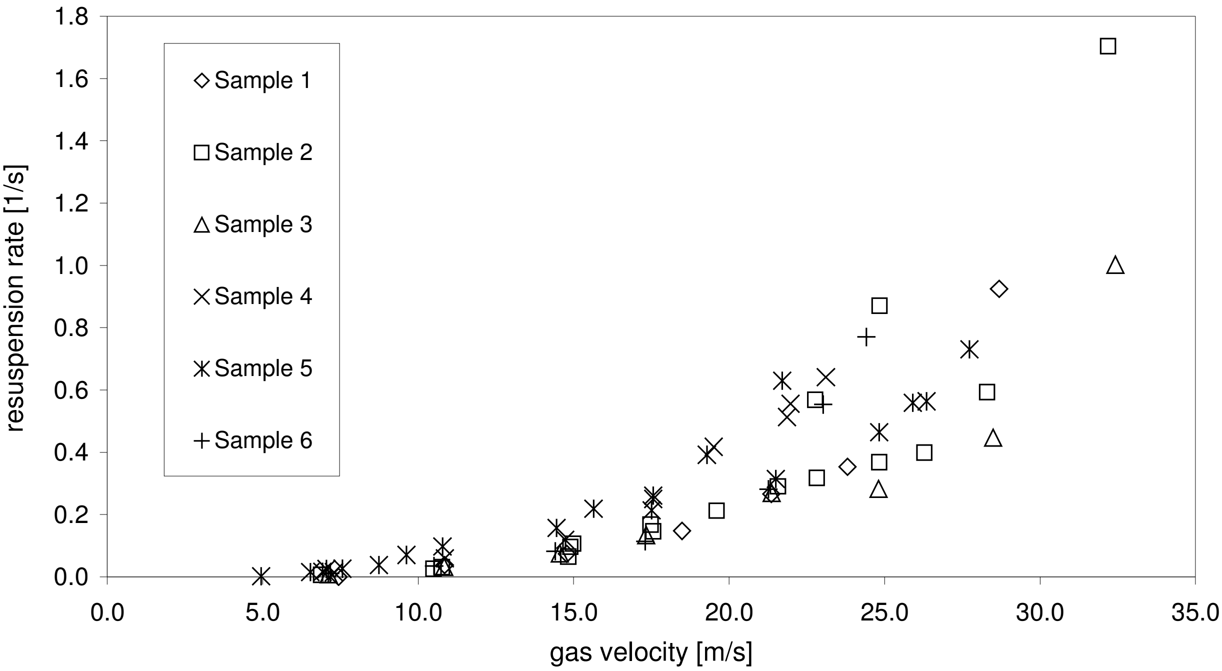

Fig. 5 – Resuspension rates of the coal dust samples as a function of gas velocity, calculated with the logarithmic formula applied to the experimental results of SOFFIA.

Another key-issue of the experimental campaign was the characterization of the multi-layer deposit behaviour as regards the resuspension rate. As a matter of fact, even if most of particle deposits are not really mono-layer, the concept of resuspension rate can be used under the hypothesis that the whole deposit is exposed to the gas flow or can be exposed during the observation time. This assumption is usually accepted as a good approximation for the very thin deposits expected inside the nuclear power plants under accident conditions, and its use still gives satisfactory results for the current experimental databases in that field.

In the case of dust deposits of several millimeters to some centimeters found in coal transportation systems, the resuspension rate parameter, independent on the dust deposit thickness, is not easily applicable. In order to better investigate this aspect, a series of ad-hoc tests was managed within the SOFFIA experimental campaign. At given gas velocities, the removed mass of dust was measured by varying the deposit thickness up to 11 mm (average value of the whole deposit, not pressed). As summarized in the graphic of Fig. 7, a significant dependence of the resuspension rate on the deposit thickness came out. Indeed, this dependence is evident at gas velocities capable to promote the resuspension/mobilization of a significant fraction of the deposit, but not higher enough to involve the particles deeply shielded below the layers.

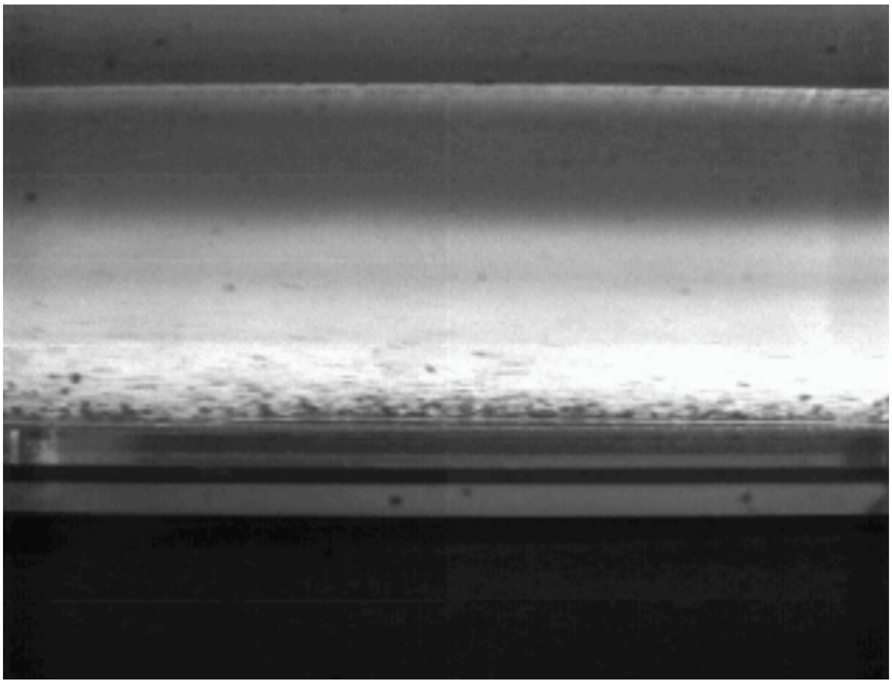

Fig. 6 – Photo taken during a resuspension experiment SOFFIA by a high speed camera (1000 frames per second, mean gas velocity 12.6 m/s, image dimensions 8.1 X 6.2 cm).

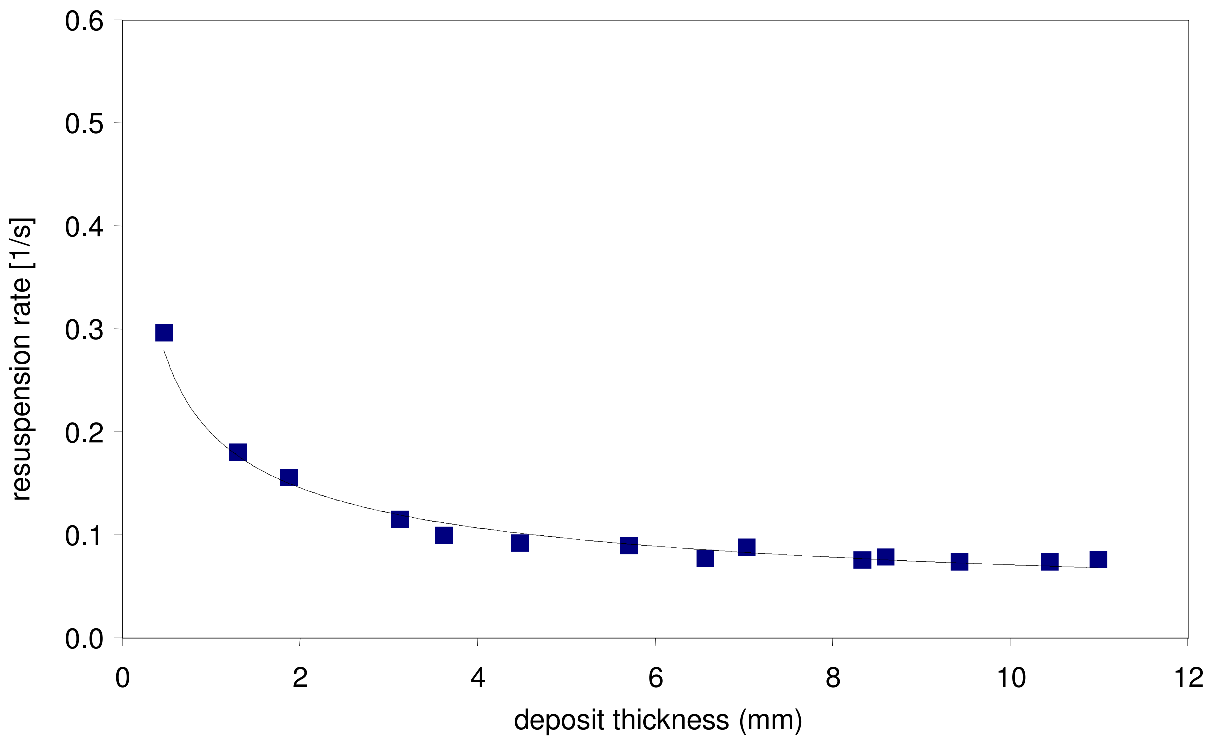

Fig. 7 – Resuspension rate of coal dust, as a function of deposit thickness, on the basis of the experimental tests SOFFIA at a gas velocity of 13 m/s.

4.0 MEASUREMENTS OF MINIMUM EXPLOSIBLE CONCENTRATION

Among the different samples collected, it was clearly possibile to notice that some of them were particularly rich in bigger particles, in comparison to the usual diameters used for dust explosion testing.

On the point of view of explosibility, it can be defined coal dust, the finest fraction, able to take part to the explosion phenomena. Of course, this definition is the most general one, but it is the starting point of the decisional process used for the preparation of the samples. It was required to choose an upper limit in terms of diameter of the samples to be tested; the criteria were mainly two: the representativity of the dust in its scenario and the concrete possibility of testing by means of the standard equipment.

Also using the help derived from the explosion experimentation in the extractive and mining fields (e.g. [5]), it was chosen as a compromise between the two criteria, to consider as coal dust the fraction of the dust below the diameter of 500 μm.

Explosion experimental determination should mostly be managed with dried materials, in order to be able to make comparisons with other campaigns.

With the aim of obtaining more representative measurements, the preparation consisted in:

- some LEL (acronym for Lower Explosible Level, synonym of MEC) measures has been made with on not dried samples, exposed to ambient air for 24 hours in thin layers (5 mm thick);
- other tests were performed with dried samples, using standard conditioning procedures;
- comparisons and confrontation were made.

The content of moisture was in any case included between 4,0 % and 4,5 %, which represents a low value, assumed to not play a significant role influencing explosions.

Tab. 2 summarizes the samples, their provenance and the preparation procedures. The differentiations on the kind of pre-test preparation is a consequence of the aims of the measurements, intended to understand the role of moisture, granulometry, provenance and ambient temperature.

Tab. 2 – Summary of the procedures for the preparation of the samples

Samples	Provenience	Particle Mean Diameter [μm]	Preparation	Scheduled tests
All	-		Removal of dust fractions with D_{eq} > 500 μm	-
C5	Conveyor belt floor	70 - 100	Exposition of 5 mm thick layers for 24 h in spacious, covered and ventilated area	LEL "as received"
			Heating at 60 °C	LEL at 60 °C
			Standard conditioning	LEL C5
			Standard conditioning and separation in granulometric fractions	LEL (D): 0-32 μm LEL (D): 32-63 μm LEL (D): 63-125 μm LEL (D): 125-250 μm
C6,7	Conveyor belt coverings	50 - 60	Standard conditioning	LEL C6,7
C8	Mill	40 – 60	Standard conditioning	LEL C8
C11	Tower floor	200 – 250	Standard conditioning	LEL C11
C12	Tower structures	130 - 160	Standard conditioning	LEL C12

For each of the test summarized in Tab. 2, the Lower Explosible Level has been measured using a 20 liters closed spherical apparatus and standard procedures [6].

For all the experimental campaign, the ignition source consisted in two chemical igniters with energy of 1 kJ each, mounted in the centre of the vessel, pointing opposite directions. Both the explosion chamber and the dust charging tank were carefully cleaned before each test. The presence of combustion residuals, unburnt particles and ashes could easily lead to misleading results.

Every series of test has been done on concentration multiples of 10 g/m^3, starting from lean mixtures and ending with the explosion of the sample. Also according to [7], it was found that precisions higher than this value had a limited significance. The Lower Explosible Level is defined as the maximum concentration at which the explosion is not registered in three tests.

For what concerns tests at higher air temperature, some other operations and cautions were needed. Water was let flow into the jacket of the vessel for 30 minutes before starting the measurements; therefore, a thermocouple could reveal a maximum temperature of 63,5 °C. Because of the operative procedures, which require repetitive air jets into and out of the vessel, the temperature used to oscillate of ± 3-4 °C around 60 °C. Every test was lead during the ascending part of the oscillation, and anyway above 60 °C.

In this case it was decided to not dry the samples, but just to heat them to 80 °C in uniform and thin layers. Just after this, the dust sample was weighted and introduced inside the dust reservoir. A new control of the temperature was performed, which showed a temperature of about 65-70 °C. From this point on, the tests were performed by means of the usual procedure. Tab. 3 shows a brief summary of the achieved results. Some non-numeric conclusions are presented below.

Moisture content: the LELs for sample C5 wet and dried were 50 and 40 g/m^3; considering the modest moisture content, this difference should probably considered to not be so big, the reason being the fact that this difference is equal to the precision of the measure.

Volatiles: it cannot be excluded that the standard drying process of the samples, often very useful in order to compare different materials or experimental campaigns, could cause a reduction of the percentage of volatiles in the samples; since this fraction is the main responsible of the ignition of the dust also according to known mechanisms [8], its role can result significant around the Minimum Explosible Concentration; it should always be remembered that this value is a limit, i.e. a quick transition between the occurrence of a phenomenon and its absence; a more specific research should be relevant indeed.

Tab. 3 – Summary of the results regarding explosibility.

Sample	Test denomination	LEL
C5	LEL "exposed to air"	50 g/m^3
	LEL "dry"	40 g/m^3
	LEL (D): 0-32 μm LEL (D): 32-63 μm LEL (D): 63-125 μm LEL (D): 125-250 μm	60 g/m^3 60 g/m^3 50 g/m^3 40 g/m^3
	LEL (T=60 °C)	50 g/m^3
C6,7	LEL C6,7	50 g/m^3
C8	LEL C8	40 g/m^3
C11	LEL C11	70 g/m^3
C12	LEL C12	50 g/m^3

Granulometry: for what concerns the tests performed on a sample divided into different granulometric fractions, one could expect the trend proper of the majority of dusts, i.e. a rise of the LEL as a function of a larger diameter. However, Fig. 8 shows a different behaviour (dotted line), also common to that found by [9] for the coal of Pittsburgh (continuous line); this also confirms the noticeable differences among coals of different provenience and parameters (ash, volatiles, mean diameter, etc.)

The reason for the different behaviour among the coal samples of this campaign and the majority of types of dust stands in the reduced capability of retaining volatiles by finer particles. This causes the lower granulometric fractions to have a higher LEL. This effect is reduced with the increasing of the diameter.

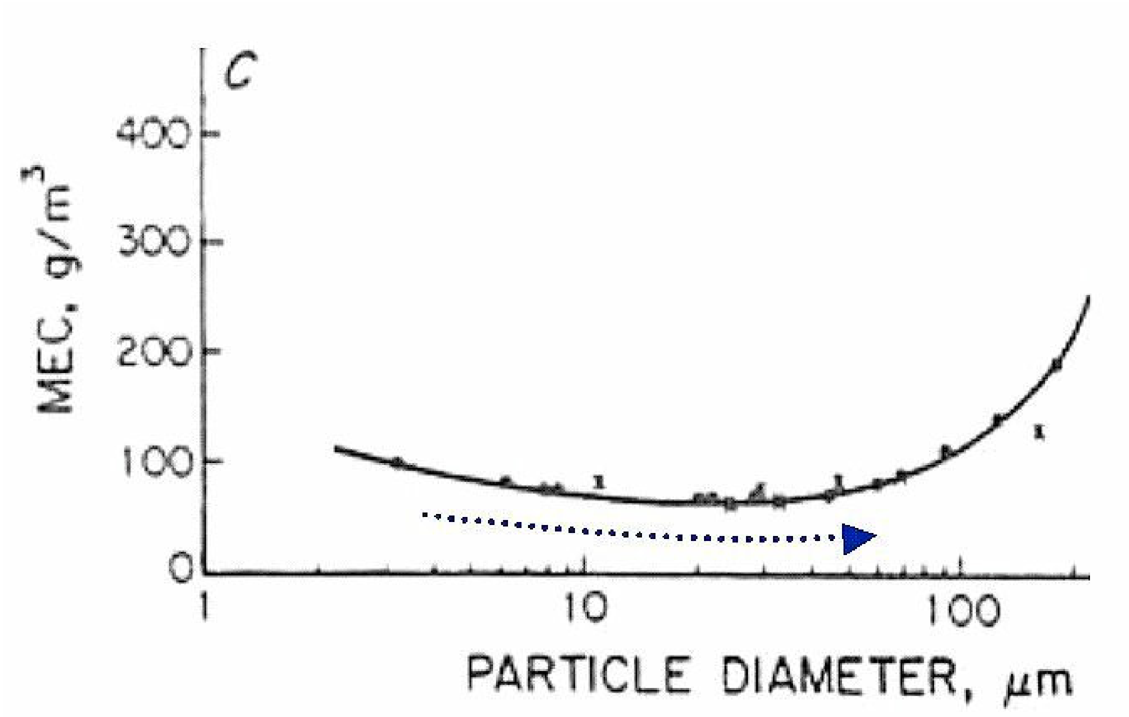

Fig. 8 - Decreasing of the LEL for different granulometric classes (dotted line), compared with the trend of the coal of Pittsburgh, from [9].

The tests performed at 60 °C (led with the mentioned procedures) showed values not very different from the tests at ambient temperature: 50 g/m^3 at 60 °C versus 40-50 g/m^3 found at 20 °C. It was consequently possible to notice the small need for tests at intermediate temperatures.

Sampling point: by analizing the results of the tests on samples C6,7, C8, C11 e C12, it was possible to register significant characterizations related to the sampling point. The dust collected over structures and walls (ligher, and therefore easier to re-suspend to higher spots) had shown lower LEL values, in comparison to those collected on the floor. It has to be observed that these last ones haven't been divided into granulometric fractions, therefore richer in dusts with a diameter higher than 250 µm, for which it is most likely that the volatiles captured on the surface of the particles played a less important role.

5.0 CONCLUSIONS

The analysis of the experimental tests indicates that the resuspension of dry coal dust deposits can occur at air speed higher than 6-7 m/s.
Also, the tests demonstrated that the adoption of the resuspension rate parameter without any corrective action to account for the multi-layered behaviour, as often used in the measurements and modellization of resuspension of radiotoxic aerosol, would lead to an overprediction of the phenomenon in the case of thick deposits.
The experiments clearly show that the mixing of air and particles is not instantaneous, as the dust particles roll and jump before being injected into the gas bulk. From the point of view of safety, this behavior can create a flow zone, close to the surface of dust deposits, having a wide range of particle concentration that can easily fall within the explosibility range, that this work confirmed to be as low as 40-50 g/m^3.

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