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▶ **To cite this version:**

Agnès Janes, Douglas Carson. Experimental study of bulk storage ignition by hot points. 14. International Symposium on Loss Prevention and Safety Promotion in the Process Industry, May 2013, Florence, Italy. pp.919-924, 10.3303/CET1331154 . ineris-00976241v2

HAL Id: ineris-00976241

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Submitted on 10 Apr 2014

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Experimental study of bulk storage ignition by hot points

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An experimental study of ignition risk due to hot points in the storage of bulk materials is required to ensure fire safety. Many parameters are involved in this phenomenon: nature of the material, storage volume and temperature, type and size of hot point, etc.
The aim of this study is to determine critical ignition temperatures of hot spots embedded in powder materials for different conditions and with several types of hot points. Materials selected for this study are pulverized coal, wood dust, cocoa powder, alfalfa, rice husks and coffee husks. Ignition tests were carried out in 1,000 and 2,700 cm^3 cubic baskets containing the combustible sample and using an inert sphere at a given initial temperature as well as a glowing cigarette butt and charcoal as ignition sources.
The critical ignition temperature is defined in terms of the hot point temperature that is able to ignite the sample. Differences between the results obtained under these test conditions have been explained by the oxy-reactivity of materials tested, different basket sizes and specific heat or heat production of hot points.
Data obtained need now to be compared to available theoretical modeling. These results will then allow the prediction of material behavior under other storage conditions.

1. Overview

Fire and explosion risk is generated by chemical or biological oxidation of combustible materials. Self-ignition is a consequence of exothermic oxidation reactions and occurs when the heat produced by oxidation is greater than that dissipated to the environment at storage surfaces. Then, the temperature increase may lead to a fire, sooner or later. The self-ignition phenomenon depends essentially on three parameters: 1) material temperature, 2) ambient temperature and 3) storage size.
Experimental characterization of self-ignition hazards in storage spaces is performed by thermal analysis of the material. Self-ignition tests in isothermal ovens lead to the critical storage size as a function of storage temperature, for a given shape. Test results are extrapolated to industrial scale by modelling using the Frank-Kamenetskii theory.
Studies on self-heating were performed in the 1920s by Semenov. They were completed by Frank-Kamenetskii (1969).
Semenov considered a homogenous temperature in the whole volume, as it appears on Figure 1. This model involves geometrical characteristics of storage spaces such as surface area and volume. However, it is not valid for large storage spaces of solids, since it does not take into account the inner and outer thermal gradients of the material.
Frank-Kamenetskii theory is more accurate. It includes the heat transfer resistance in the material. It considers that heat transfer is due to conduction inside the material, and is linked to an ideal convection at the outer surface. This model involves geometrical characteristics of the storage space and the thermal conductivity of the material.
Frank-Kamenetskii's theory does not take into account the surface heat resistance, unlike Thomas and Bowes's -theory (Bowes, 1984). Indeed, Thomas and Bowes consider simultaneously the heat transfer resistance into the material and the surface heat resistance. This model is the most complete and introduces the thermal conductivity of the material, the shape and finally convection and radiation parameters at the interface, using the Biot number (α). It corresponds to the ratio of conduction and convection coefficients.

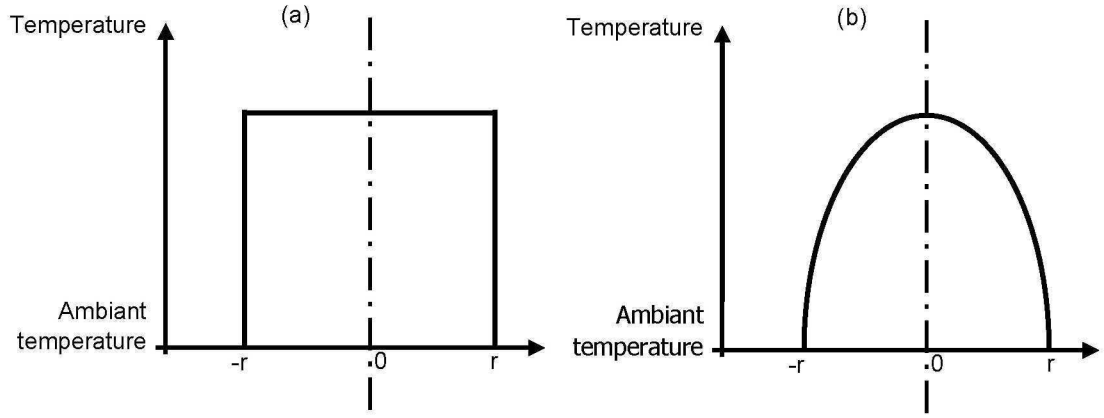


Figure 1: Shape of theoretical temperatures in Semenov (a) and Frank-Kamenetskii (b) models

In the case of heating by a hot spot, the initial heat contribution is not due to self-heating. Some examples can be found in industrial situations (Carson, 1991; Krause and Schmidt, 2000):

- Hot spot of inert material at a given initial temperature introduced into powder storage. It may be metal particles introduced accidentally in a hot storage or mechanical sparks,
- Hot spot of combustible material at a given initial temperature introduced into powder storage. This can be linked to a part of the storage locally overheated because of a failure of temperature regulation of a dryer, or even a cigarette butt,
- Hot spot of inert material maintained at a given temperature. This corresponds to a limit case of the first two points: very high heat capacity of the inert material or reaction rate of the oxidation limited by oxygen diffusion. This could correspond to the case of surfaces heated by outside: welding or an electrical equipment. Modelling of this phenomenon was recently proposed for the specific case of metallic powders (Chunmiao et al., 2013).

2. Experimental

A previous study performed at INERIS (Janès et al., 2011) was devoted to design and validate an experimental protocol to measure the critical ignition temperature by a hot point of bulk storage of coal dust, in baskets cube of variable size. Hot points used were a steel sphere of 30 mm diameter and heating steel cylinders of 6.5 and 10 mm diameter.

The objective of the experimental setup protocol that was developed is ultimately to show the relationship between the storage size of a bulk material and the critical temperature of a hot spot located in the center of the storage. Thus, it is necessary to test other experimental conditions, by varying the nature and the size of the hot spot and testing other materials. Tests were performed on the six materials listed in table 1.

Table 1: List of materials selected for the tests

Material	Particle size	Humidity
Wood dust	33.1 % > 315 µm (sieving)	0 rel. % (dried before testing)
Lucy coal	Median: 29 µm (LASER diffraction)	1.4 rel. %
Cocoa powder	Median: 8 µm (LASER diffraction)	2.9 rel. %
Alfalfa	100 % > 315 µm (sieving)	0 rel. % (dried before testing)
Rice husks	100 % > 315 µm (sieving)	9.3 rel. %
Coffee husks	100 % > 315 µm (sieving)	14.2 rel. %

The critical ignition temperature by hot spots is determined in 1,000 and 2,700 cm^3 cubic baskets. Tests are performed into a 125 L ventilated oven, regulated at 27 °C.

Cubic baskets are made, except their upper face, of 10 µm wire mesh. This is sufficiently fine to avoid sieving, but does not restrain the oxygen diffusion.

Hot spots used are represented on figure 2 below:

- An incandescent cigarette butt,
- An incandescent oak charcoal,
- A steel sphere of 10 mm diameter, preheated in an oven.

Some preliminary tests showed a surface temperature of these three hot points near 310 °C.



Figure 2: View of the three types of hot points used

Each test is performed using a clean and dry cubic basket. The amount of coal introduced in the basket is weighted. Then, the coal is introduced into the basket, without compaction.
The K-thermocouples are placed into the basket before introduction of the sample and the hot point, preventing its cooling. Location of thermocouples in the basket is represented on Figures 3 and 4.
The sphere is heated in a furnace regulated at 450°C. When the test temperature is reached, it is then moved over in the full basket. In the case of cigarette butt and oak charcoal, the heating is obtained using an ignited propane torch.
After the start of the test, the temperatures into the basket are measured as a function of time. When the temperatures strongly increase and go over the hot point for at least 50 °C, it can be considered that an ignition occurs.
When the temperatures grow up and go over hot point temperature, but stabilize in a plateau at the hot point temperature, ignition does not occur.

Some previously tests showed a +/- 5 °C repeatability of this method.

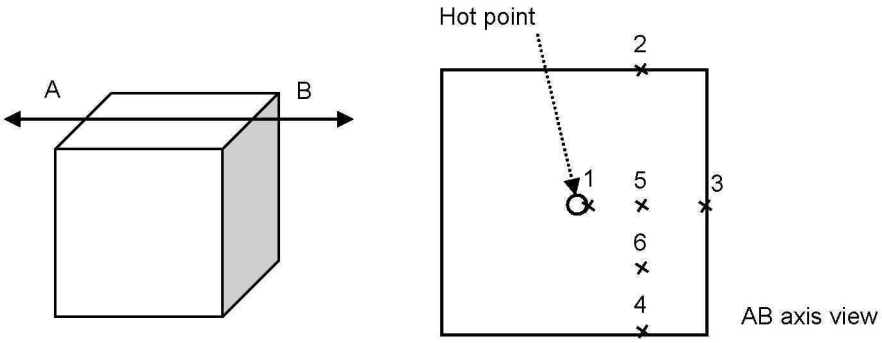


Figure 3: Location of temperature measurement points inside the 2,700 cm^3 baskets

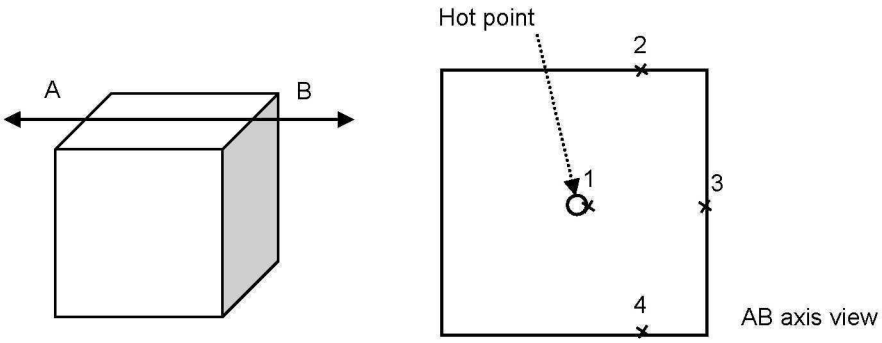


Figure 4: Location of temperature measurement points inside the 1,000 cm^3 baskets

Note: T1 is not representative of the hot point temperature, since there is a thickness of a few mm of bulk material between the hot point and the thermocouple.

3. Results

Table 2 indicates the experimental conditions associated to tests performed.

Table 2: List of tests performed

Test #	Material	Hot point	Basket size (cm^3)	Initial weight (g)	Mass loss (%)	Maximal temperature in the material (°C)	Result
1	Lucy coal	Cigarette butt	1,000	576	0	40	No ignition
2	Alfalfa	Oak charcoal	2,700	218	4	164	No ignition
3	Wood dust	Heated sphere	1,000	3,3	98	680	Ignition
4	Wood dust	Heated sphere	2,700	7,4	99	651	Ignition
5	Lucy coal	Heated sphere	1,000	579	0	141	No ignition
6	Lucy coal	Heated sphere	2,700	1584	0	62	No ignition
7	Cocoa powder	Heated sphere	2,700	No measured	>50 %	605	Ignition
8	Alfalfa	Heated sphere	2,700	24	88	679	Ignition
9	Rice husks	Heated sphere	2,700	235	0	59	No ignition
10	Coffee husks	Heated sphere	2,700	506	0	277	No ignition

The evolution of measured temperatures is recorded on Figures 5 and 6, given as examples.

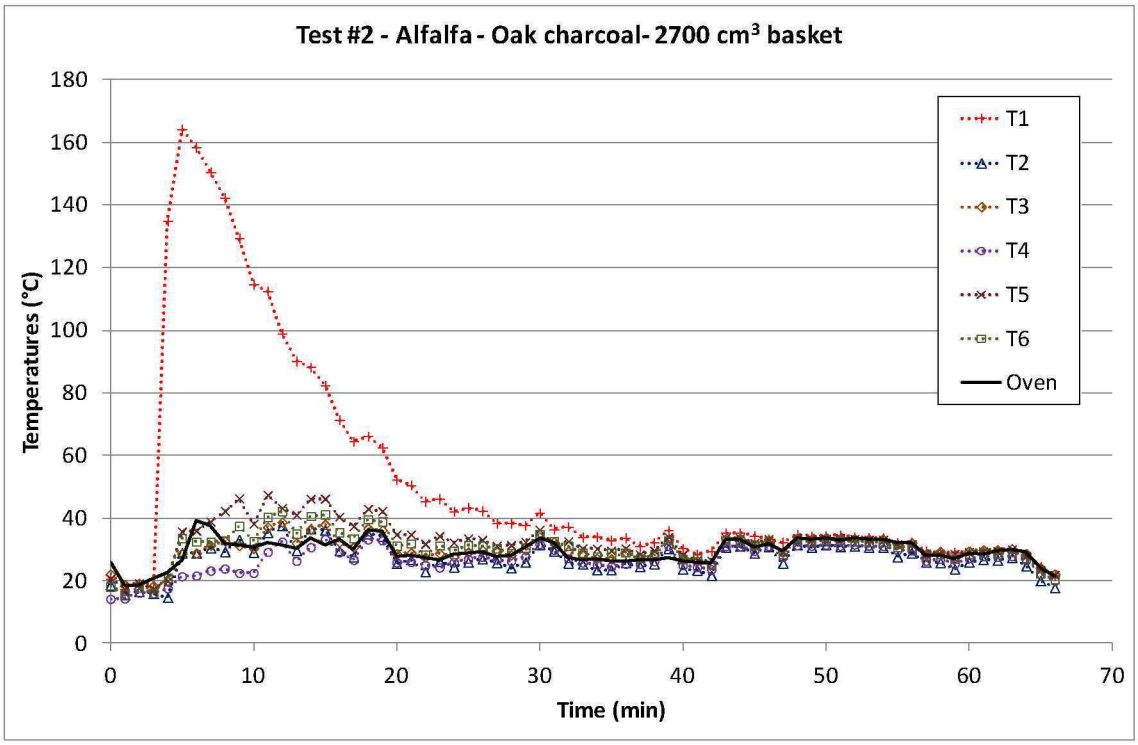


Figure 4: Temperature measurements observed during test #2

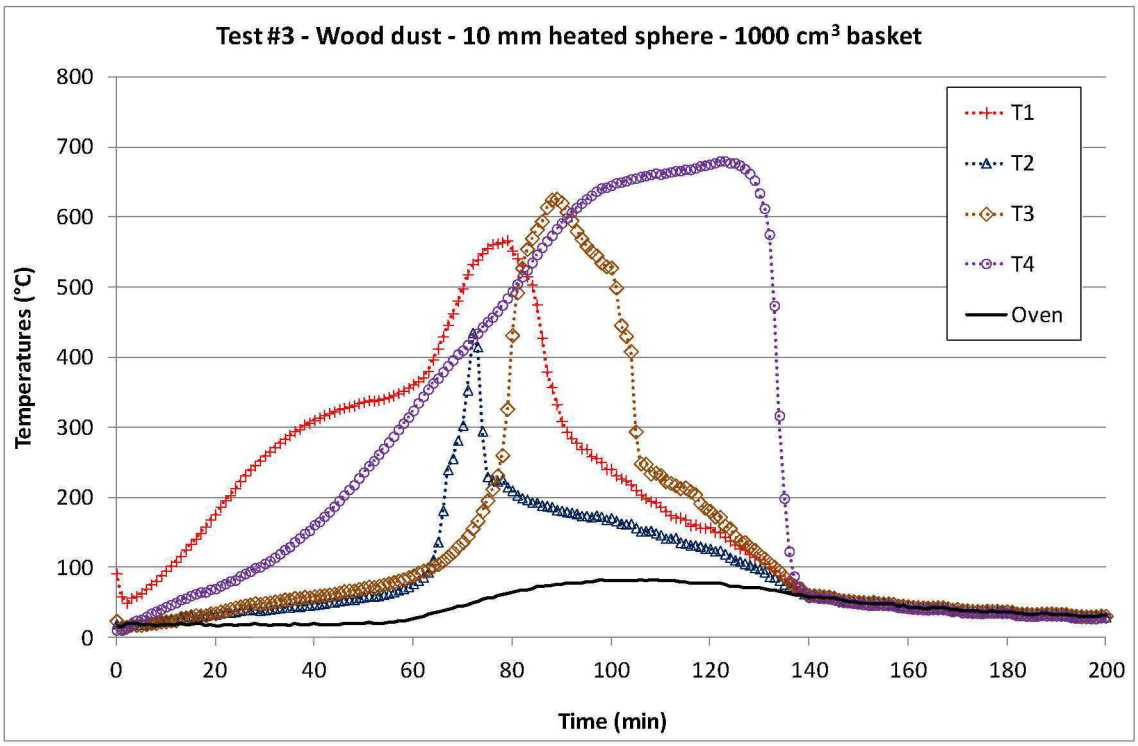


Figure 5: Temperature measurements observed during test #3

4. Discussion

Tests performed with cigarette butt and oak charcoal did not lead to an ignition of material tested. These hot spots were located in the center of the basket. The limited oxygen diffusion up to the combustible hot point was not enough to permit the propagation of the combustion to the material tested and the hot point was progressively cooling. Indeed, the amount of energy transmitted from the combustible hot spots to the materials tested was not sufficient to initiate their combustion, unlike the case of heated inert sphere of 10 mm diameter, at the same temperature. This is related to the fact that in the case of combustible hot spots, only a small volume was heated, comparatively to the heated sphere. Furthermore, the heat capacity of the combustible hot spots is much lower than that of the steel sphere, for which ignition were observed. These tests show that, although the material tested is very oxy-reactive, an ignition does not occur when a small combustible hot point is introduced into bulk storage.

The basket size, 1,000 or 2,700 cm^3, does not appear as an influencing parameter on test results. Indeed, coal does not ignite in both cases. However, wood dust was ignited with the two tested basket size.

The induction time, which corresponds to the delay between the introduction of the hot spot and the ignition, is variable depending on the material tested and the basket size.

In the case of 2,700 cm^3 basket tests, an ignition is obtained in a few minutes for alfalfa dust. The induction delay observed for the same basket size is much higher for wood dust and cocoa powder, since it reaches up 2 to 3 h. The induction delay is related to the thermal conductivity and heat capacity of the test product, in addition to its reactivity.

5. Conclusion

The aim of this paper was to describe an adapted experimental protocol to determine ignition temperatures of powders under different conditions and with several types of hot points. The first results demonstrate that this protocol is relevant.

Discrepancies between the results obtained under these different test conditions have been explained considering basket sizes and hot points geometry. However, other test conditions should be experimented to acquire more data. For example, the ignition using an inert hot point at a given heating flow was not tested.

These different test conditions will allow the simulation of industrial situations of incident such as the presence of an appliance power supplied or an incandescent particle in a storage space like a silo. It will then be possible to compare data obtained to available theoretical modelling.

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