



Correlation between self-ignition of a dust layer on a hot surface and in baskets in an oven

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ABSTRACT

Evaluation of self-ignition hazard of bulk materials requires experimental determination of self-ignition temperatures as a function of volume. There are two standardised methods: (1) determination of the self-ignition temperature of dust samples in oven and (2) measurement of the self-ignition temperature of a dust layer deposited on a hot surface. Sometimes, the sample behaviour during these tests makes the second method difficult to apply.

The self-ignition phenomena in these two tests rely on the same principles. Their results are interpreted with the help of theoretical relations. The correlation described in this paper can be considered acceptable to deduce self-ignition temperature of a dust layer, based on results of self-ignition of the same dust in heating ovens, if the Biot number (α) can be estimated. Uncertainty on the correlation is near 30 K. This uncertainty is on the same order of magnitude as the difference in the self-ignition temperature on a hot surface for thickness between 5 and 15 mm.

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1. Introduction

Self-ignition is a common source of ignition of porous storage of bulk materials such as powders and dusts. Evaluation of this ignition hazard, taking into account manufacturing or storage conditions, requires experimental determination of critical self-ignition temperatures as a function of volume.

One of the first standardised tests [1] consists of measuring the minimum temperature of a flat hot surface which results in the ignition of a dust layer of a given thickness, which is generally 5 mm. This test is particularly relevant for industries where dust is handled and can accumulate on potentially hot surfaces. However, this test is not always easy to carry out when the dust is blown away due to air movement or when the layer cracks due to the hot surface. Thus, when testing a 5-mm layer is not possible, the same test can be carried out with a thicker dust layer. Consequently, as we know [2], the self-ignition temperature will be lower than that of a 5 mm layer. This was more recently reported by El-Sayed [3].

A second test is used to determine critical self-ignition temperatures. Bulk materials are placed in several baskets of various sizes, which are placed in a heating oven. So far, according to a theoretical model, relation between self-ignition temperature and bulk storage size can be found. This second method is easier to conduct

than the previous one. This second method is also used to classify self-ignition substances for the transport of dangerous goods [4]. This classifying methodology was discussed in the past [5] and [6].

Phenomena highlighted in these two tests are similar and their results can be connected with theoretical relations.

The aim of this paper is to describe a correlation model between both methods. Then, results of an experimental validation campaign are presented and discussed.

2. Context

Since application of European directive 1999/92/EC [7], several actions must be taken by employers. It includes:

- evaluation of explosive atmospheres¹ hazards,
- classification of area where explosive atmospheres may occur,
- identification of technical and/or organisational explosion control measures,
- use of appropriate electrical and non-electrical apparatuses according to area classification,
- set-up and regular update of the so called “explosion protection document”.

¹ “Explosive atmosphere” means a mixture with air, under atmospheric conditions, of flammable substances in the form of gases, vapours, mists or dusts in which, after ignition has occurred, combustion spreads to the entire unburned mixture [4].

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Nomenclature

A	pre-exponential factor of Arrhenius equation (s^{-1})
E	apparent activation energy ($J mol^{-1}$)
h	global heat transfer on storage surface (convection and radiation) ($W m^{-2} K^{-1}$)
M	lumped parameter (which depends on parameters such as heat of combustion, heat capacity, density)
P	lumped parameter (K)
Q	heat of reaction per unit mass ($kJ kg^{-1}$)
r	critical dimension (half-edge length of cubic basket at the self-ignition temperature) (m)
R	universal gas constant, $8.314 (J (mol K)^{-1})$
T_a	room temperature (K)
T_c	self-ignition temperature of a given sample volume (K)
T_e	isothermal oven temperature (K)
T_p	hot plate temperature (K)
T_s	upper surface temperature (K)
T_0	storage's central point temperature (K)
z	critical dimension (half-thickness of the layer at the self-ignition temperature) (m)

Greek symbols

α	Biot number
δ_c	Frank-Kamenetskii parameter for heating oven tests, 2.6 for a cubic storage
δ_{cp}	Frank-Kamenetskii parameter for hot plate tests
λ	thermal conductivity of material ($W m^{-1} K^{-1}$)
ρ	density ($kg m^{-3}$)

Explosion hazards assessment shall take into account the likelihood that ignition sources will be present and become active and effective. Thus, substances used and their ignition probability shall be considered to select safe work equipment and safe working conditions.

As far as electrical apparatuses are concerned, EN 1127-1 standard [8] sets two specifications for devices. One is about dust permeability and the other concerns limitation of surface temperature.

Indeed, this standard considers that apparatuses can be safely operated when dust is present, if its maximum surface temperature is:

- lower than the two thirds of dust self-ignition temperature in cloud, and
- lower than the self-ignition temperature of a 5-mm layer minus 75 K.

So far, reliable methods are needed to determine self-ignition temperatures in order to demonstrate the safe use of equipment. Standards applied in this study are:

- EN 50281-2-1 [1]: Electrical apparatus for use in the presence of combustible dust – Part 2-1: Test methods – Methods for determining the minimum ignition temperature of dust,
- PrEN 15188 [9]: Determination of the spontaneous ignition behaviour of dust accumulations.

3. Self-ignition modeling

Self-ignition is related to exothermic oxidation reactions within the mass of bulk particle storage.

When the storage conditions do not allow complete dissipation of heat generated by these slow going oxidation reactions by the means of a sufficient heat exchange between reactional system and external environment, a rise of temperature within the mass is observed.

Three parameters are predominant for self-ignition phenomenon:

- product temperature, in regard to ambient temperature,
- storage size,
- oxygen diffusion conditions through the storage.

Models of self-ignition were developed in the 1920s by Semenov. This work was then continued by Frank-Kamenetskii [10] and later by Thomas [11].

A comparison of Semenov and Frank-Kamenetskii theories was recently proposed by Shouman [12].

Semenov's model considers an equal temperature throughout the volume, as shown in Fig. 1a. It is based on geometrical dimensions, surface and volume of storage. Since this model does not take into account heat gradients between centre and periphery, it is not valid for large size storage.

Frank-Kamenetskii's model takes into account a temperature gradient inside the sample, which depends on its geometrical dimensions and thermal conductivity. In this model, heat transfer is achieved by optimal conduction into the material, and by convection and radiation on the storage periphery. In this case, as shown in Fig. 1b, surface temperature is equal to ambient temperature.

This last hypothesis implies a high and global coefficient of heat transfer on the storage surface. If not, the surface temperature remains higher than ambient temperature.

Finally, Thomas and Bowes' model [2] takes into account both internal thermal resistances by conduction and external thermal resistance by convection and radiation. This theory considers thermal conductivity of material, geometrical dimensions of storage as well as parameters of convection and radiation at the interface between material and air. The relation between thermal conduc-

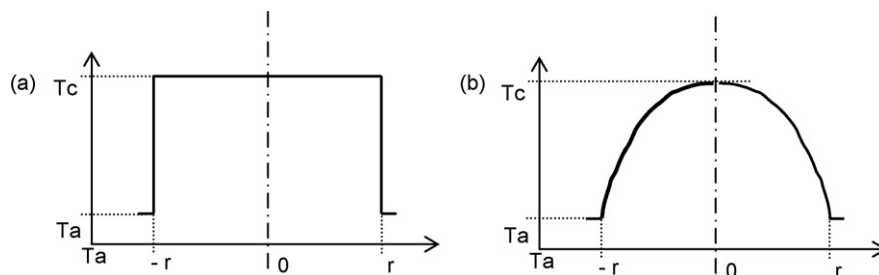


Fig. 1. Allure of theoretical temperatures in Semenov (a) and Frank-Kamenetskii (b) models.

tion inside the storage and convection on the surface is given by Eq. (1) [2], which uses the Biot number (α).

$$\alpha = \frac{hr}{\lambda} \quad (1)$$

Biot number depends on storage size. It tends towards 0 when storage size tends towards 0 for equal values of global heat transfer coefficient on storage surface and thermal conductivity inside the sample.

When thermal conductivity of material is high compared to exchange coefficient on surface, Biot number tends also towards 0. In this case, internal temperature of sample is homogeneous and higher than ambient temperature, that correspond to Semenov's theory.

On the contrary, if thermal conductivity of material is low compared to heat transfer on surface, Biot number tends towards infinite, that corresponds to Frank-Kamenetskii's model.

If there is an equal repartition of heat transfer resistance between inside storage conduction and outside convection and radiation, Biot number is equal to 1.

4. Correlation between self-ignition of a dust layer and self-ignition in an oven

Critical self-ignition temperature is determined for different sizes of cubic latticed baskets in isothermal ovens, which are filled by samples, as it is described in Pr EN 15188 standard [9]. Experimental results take the form of couples of data (r , T_c) where r is the half-edge length of cubic basket and T_c the critical self-ignition temperature, for each sample.

These values are introduced in the model written as shows Eq. (2) [2].

$$\ln \left[\frac{\delta_c T_c^2}{r^2} \right] = M - \left(\frac{P}{T_c} \right) \quad (2)$$

where $M = \ln[(EQ\rho A)/(R\lambda)]$, $P = E/R$. Notes: \ln is the Napierian logarithm, M and P parameters can be calculated by linear regression (least square method).

To make Eqs. (2) and (3) be rigorous, it is necessary to add a multiplication coefficient equal to 1 ($K^{-2}m^2$) in the expression $(\delta_c T_c^2)/r^2$.

In the particular case of a layer deposited on a hot surface, ambient temperature is not homogeneous and the heating is unsymmetrical.

The temperature of the layer in contact with the hot surface is equal to hot surface temperature itself, while the external layer surface temperature can be calculated with ambient temperature and Biot number, according to equations (3) and (4) [2]:

$$\ln \left[\frac{\delta_{cp} T_c^2}{r^2} \right] = M - \left(\frac{P}{T_c} \right) \quad (3)$$

δ_{cp} is calculated according to equation (5) below:

$$\delta_{cp} \approx \frac{1}{2} \left(\frac{\alpha}{1+2\alpha} \right)^2 \left(1.4 + \frac{E}{RT_p^2} (T_p - T_a) \right)^2 \quad (4)$$

The validity conditions of Eq. (4) are [2]:

- $(E/RT_p^2)(T_p - T_a) > 8$, and
- $\alpha > 0.5$.

In the case of self-ignition by a hot surface, the geometrical constant depends on several parameters, such as apparent activation energy (E), ambient temperature (T_a), hot surface temperature (T_p) and geometry of the deposit and efficiency of heat transfer between hot surface and dust layer. On the contrary, in the case of self-ignition

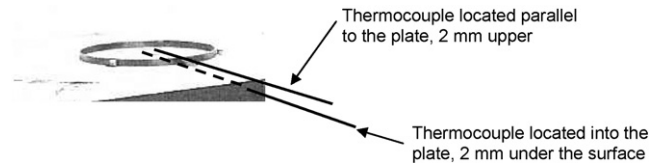


Fig. 2. Schematic view of the location of thermocouples while self-ignition tests on hot surface.

in an isothermal oven, the geometrical constant depends only on geometry of the basket.

By dividing Eq. (4) by Eq. (2), for the condition T_e (determination of self-ignition temperature by isothermal oven method) = T_p (determination of self-ignition temperature by hot surface method), equation (5) is obtained:

$$\frac{z}{r} = \frac{\sqrt{\delta_{cp}}}{\sqrt{\delta_c}} \quad (5)$$

Development of Eq. (5) leads to Eq. (5').

$$r = \frac{2.28z}{\left(\frac{\alpha}{1+2\alpha} \right) \left(1.4 + \frac{E}{RT_p^2} (T_p - T_a) \right)} \quad (5')$$

Eq. (5') gives the half-size of a cube tested in isothermal oven, which corresponds to the half-thickness of a layer deposited on a hot surface for which the self-ignition temperature is equal to the self-ignition temperature of the cube.

Prediction of the critical temperature of a dust layer deposited on a hot surface can be done by plotting Eq. (5') on a graph. The intersection point with the curve obtained by isothermal oven test, for the same sample, gives the theoretical self-ignition temperature of a layer on a hot surface.

5. Apparatus and procedure

5.1. Ignition of a dust layer deposited on a surface heated at a constant temperature

The minimum ignition temperature of a dust layer of specified thickness is the lowest temperature of a hot surface at which ignition occurs. According to EN 50281-2-1 [1] standard, determination of this temperature needs a heating electric resistance, with a metallic plate disposed on it. The maximum temperature of the plate used in this study is 450 °C.

Dust layer is prepared by filling the cavity formed by a metal ring of appropriate height, placed on the heated surface and by levelling the layer on the top of the ring. This ring, which internal diameter is equal to 100 mm, is left in place during the test.

A given dust is tested in a layer of 5.0 ± 0.1 mm depth. Two other depths are also studied: 12.5 ± 0.1 and 15.0 ± 0.1 mm.

Several temperature measurements are carried out during a test (Fig. 2):

- ambient temperature, with a thermocouple² placed at 1 m of the heated surface but shielded from heat convection and radiation from the surface,
- dust layer temperature, with a thermocouple stretched across the heated surface, parallel to it, 2 mm height from it, with the hot junction over the centre of the plate,
- heated surface temperature, with a thermocouple disposed inside the heated plate mass, parallel to it and with the hot junction on the centre of the plate.

² All temperature measurements in this study use chromel–alumel (K) thermocouples.



Fig. 3. View of the ignition of a 5 mm metallic dust layer during a self-ignition test.

The dust is put into the ring with a spatula and spread without compressing.

For the determination of the minimum ignition temperature of a layer of a given thickness, repeated trials are carried out, using a fresh layer of dust for each trial and with up-and-down adjustments to the temperature of the heated surface.

Ignition is considered to have occurred if:

- visible glowing or flaming is observed, or
- a temperature of 450 °C is reached, or
- a temperature rise of 250 K above the temperature of the heated plate is measured.

Fig. 3 shows ignition of a 5 mm zinc dust on the heating surface.

On the contrary, if none of these three conditions is satisfied after a 30 min delay, ignition is not considered to have occurred. This non-ignition test is repeated two times.

Trials are made until the ignition temperature is framed by a temperature value for which ignition is observed and another for which no ignition has occurred. These two values must not be different by more than 10 K. The experimental ignition temperature of the dust layer is the lowest temperature.

We consider that these apparatus and procedure lead to an uncertainty of +4.5 K/–14.5 K [13].

5.2. Self-ignition of dust in ovens

Critical self-ignition temperatures for different size of cubic baskets are determined by successive trials in heating ovens.

According to the Frank-Kamenetskii's model, relation between self-ignition temperature and storage size can be set. Then, extrapolation from this relation can help, for different storage geometry to evaluate:

- the critical size (maximum size) of a storage for a specified temperature, which is particularly useful for low temperatures,
- the critical storage temperature (maximum temperature) for specified size and geometry.

According to PrEn 15188 [9], critical self-ignition temperatures are assessed using 125 L re-circulating air ovens, with a maximum temperature of 300 °C and equipped with a middle-height grid, as shown in Fig. 4. Ventilation is provided to exhaust any gases released from the dust.

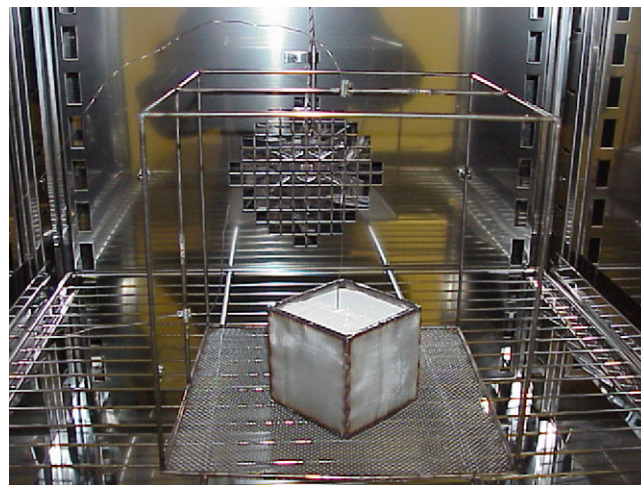


Fig. 4. View of a filled basket inside a heating oven.

The dust sample is filled into mesh wire baskets of different sizes with a spatula, without compressing and levelled on the top. Baskets are open at the top and closed at the bottom. The width of the mesh used, made of stainless steel, is equal to 10 μm, in order to avoid sifting but to allow oxygen diffusion. Volumes used in this study are 8, 125, 343 and 1000 cm³, so critical sizes of cubic baskets (half height) are 1, 2.5, 3.5 and finally 5 cm.

These baskets, being filled by the sample, are located on the centre of the oven preheated to the test temperature.

Two temperature measurements are made during a test (Fig. 5):

- oven temperature, with a thermocouple freely installed in the air space at half distance between the sample surface and the inner wall of the oven. Tests have shown that maximum temperature difference between two points in an oven is about 2 K [13],
- sample temperature, with a thermocouple located with its hot junction directly at the centre of the sample.

If sample temperature, after an induction delay, grows abruptly and rises at least 60 K above the oven temperature, it is considered that self-ignition is occurring. On the contrary, we assume that self-ignition did not occur if sample temperature is remains close to oven temperature after an induction delay or exceed it of a few K.

A sufficient number of tests is carried out with a fresh dust sample for each trial, until the oven temperature is high enough to cause ignition of the sample but which is no more than 5 K higher than a temperature which fails to cause ignition.

Critical temperature, for a specified basket size, is equal to the middle value of the interval framed by these two previous temperatures. We consider that the undertaking of the procedure described lead to an uncertainty of ±8.0 K [13].

When critical temperatures are obtained for the four baskets sizes, these experimental points can be correlated. For each of the

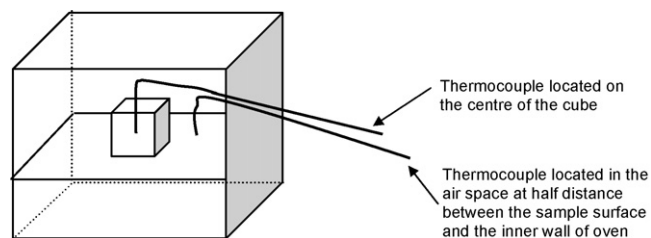


Fig. 5. Schematic view of the location of thermocouples while self-ignition tests in ovens.

four couple of data (r, T_c) obtained, two coefficients (A, B) are calculated, according to Eqs. (6) and (7) below:

$$A = \text{Ln} \left(\frac{2.6T_c^2}{r^2} \right) \quad (6)$$

$$B = \frac{1}{T_c} \quad (7)$$

Notes: Ln is the Napierian logarithm, 2.6 is the value of the Franck-Kamenetskii parameter for a cubic storage (δ_c).

According to the previous equation (2) (see also Section 4) below [2], the plot of the four points (A, B) describes a line:

$$\text{Ln} \left[\frac{\delta_c T_c^2}{r^2} \right] = M - \left(\frac{P}{T_c} \right)$$

M and P parameters are then calculated by linear regression (least square method).

6. Protocol selected for experimental correlation

In order to check experimentally the correlation between the results of self-ignition in ovens and self-ignition on heated surfaces, we proceeded as follow, for each of the 14 samples tested.

1. self-ignition tests in heating ovens, for the four sizes of cubic baskets and calculation of M and P parameters by correlation of experimental results,
2. calculation of geometrical constant (δ_{cp}) and self-ignition temperature of dust layers by graphical determination, for three different layer thickness (5, 12.5 and 15 mm) and three different values of Biot number (infinite, 1 and 1/2),
3. experimental determination of self-ignition temperature of dust layers, for the three different layer thickness (5, 12.5 and 15 mm) of each sample,
4. comparison of experimental and theoretical results, for the three values of Biot number.

We worked with three values of Biot number, as follows:

- $\alpha = \text{infinite}$ (heat transfers limited by conduction): conditions of Frank-Kamenetskii's model,
- $\alpha = 1$ (heat transfers limited by conduction and convection): conditions of Thomas and Bowes' model,
- $\alpha = 1/2$: theoretical limit of Thomas and Bowes' model.

Table 1
Results of self-ignition tests in heating ovens

Ref.	Samples	Self-ignition temperatures in heating ovens (°C)			
		8 cm ³ cubic basket	125 cm ³ cubic basket	343 cm ³ cubic basket	1000 cm ³ cubic basket
1	Purifying station mud dust	187	147	137	127
2	Wheat dust no. 1	222	187	147	142
3	Potatoes powder	202	172	167	157
4	Crushed waste dust	202	177	167	157
5	Zinc powder	>300	277	262	252
6	Cacao powder	187	157	147	137
7	Wood and flax dust	227	192	182	172
8	Activated carbon dust	>300	292	252	242
9	Wheat dust no. 2	222	182	172	162
10	White wood dust	232	197	182	172
11	Wood with asphalt dust	222	187	172	162
12	Wheat dust no. 3	222	187	177	162
13	Persulphate powder	132	102	97	82
14	Coal dust	222	167	147	132

7. Results and discussion

Results of self-ignition tests in heating ovens are shown in Table 1. Tables 2–5 show differences between experimental and theoretical results of self-ignition temperatures of dust layers.

7.1. Influence of Biot number (α) on theoretical self-ignition temperatures

Comparison of theoretical values is shown in Table 5. It shows that, for a given dust layer thickness, the calculated self-ignition temperature increases with α value. Table 5 points out that the difference between theoretical values of self-ignition temperatures is influenced either by dust layer thickness or by the nature of the sample. One exception is noticed: in the case of the activated carbon dust, the variation is significantly higher when α value is modified. This could be explained by the high value of carbon dust specific surface, in comparison with the others. This influences the value of the M and P global parameters when calculating theoretical self-ignition temperatures.

7.2. Difference between experimental and theoretical self-ignition temperatures

Differences between experimental and theoretical self-ignition temperatures are shown in Tables 2–4. Accuracy of correlation obtained is illustrated on these tables by colouring: the darker, the less accurate correlation.

In a general basis, experimental results for 5 mm dust layers agree with theoretical previsions, excepted for two varieties of wheat dust (nos. 1 and 3) and for the zinc powder. Calculated self-ignition temperatures are higher than experimental values for two thirds of the tested samples. The best correlation (difference lower than 10 K) are obtained with a α value equal to 1 (5 cases out of 11).

Theoretical prevision under-estimates the experimental self-ignition temperature of 12.5 mm dust layers for every samples tested. Temperature differences are systematically higher are than 10 K. The closest calculated temperature to the experimental one is obtained when α value tends to infinite. The worse correlation is obtained for one variety of wheat dust (no. 2).

Calculated self-ignition temperatures for 15 mm layers are lower than experimental values for 80% of tested samples. The best correlation (difference lower than 10 K) are obtained when α value tends to infinite (3 cases of 7). The worse correlation is obtained for the coal dust.

Table 2

Difference between theoretical and experimental self-ignition temperatures for 5 mm layers

Ref.	Samples	Experimental results (in °C) for 5 mm layers	Difference between prevision and experimental values (in K) for 5 mm layers		
			between $\alpha = 1$ and experimental	between α infinite and experimental	between $\alpha = \frac{1}{2}$ and experimental
1	Purifying station mud dust	273	9	37	-9
2	Wheat dust n°1	300	80	133	46
3	Potatoes powder	300	-20	-4	-34
4	Crushed waste dust	280	0	18	-12
5	Zinc powder	280	150	174	134
6	Cacao powder	270	0	20	-14
7	Wood and flax dust	340	-18	4	-36
8	Activated carbon dust	> 450	Values not calculable		
9	Wheat dust n°2	> 450	Values not calculable		
10	White wood dust	333	5	31	-15
11	Wood with asphalt dust	333	-7	19	-27
12	Wheat dust n°3	297	25	51	13
13	Persulphate powder	177	29	49	13
14	Coal dust	Experimental value not determined			

Values are not calculable when experimental temperature is higher than 450 °C. Coloration represent the accuracy of correlation obtained: the more darkly, the less accurate correlation.

Table 3

Difference between theoretical and experimental self-ignition temperatures for 12.5 mm layers

Ref.	Samples	Experimental results (in °C) for 12.5 mm layers	Difference between prevision and experimental values (in K) for 12.5 mm layers		
			between $\alpha = 1$ and experimental	between α infinite and experimental	between $\alpha = \frac{1}{2}$ and experimental
1	Purifying station mud dust	Experimental value not determined			
2	Wheat dust n°1	Experimental value not determined			
3	Potatoes powder	280	-38	-22	-48
4	Crushed waste dust	Experimental value not determined			
5	Zinc powder	Experimental value not determined			
6	Cacao powder	260	-34	-16	-46
7	Wood and flax dust	320	-46	-26	-60
8	Activated carbon dust	> 450	Values not calculable		
9	Wheat dust n°2	390	-122	-98	-136
10	White wood dust	Experimental value not determined			
11	Wood with asphalt dust	Experimental value not determined			
12	Wheat dust n°3	Experimental value not determined			
13	Persulphate powder	Experimental value not determined			
14	Coal dust	Experimental value not determined			

Values are not calculable when experimental temperature is higher than 450 °C. Coloration represent the accuracy of correlation obtained: the more darkly, the less accurate correlation.

Table 4
Difference between theoretical and experimental self-ignition temperatures for 15 mm layers

Ref.	Samples	Experimental results (in °C) for 15 mm layers	Difference between prevision and experimental values (in K) for 15 mm layers		
			between $\alpha = 1$ and experimental	between α infinite and experimental	between $\alpha = 1/2$ and experimental
1	Purifying station mud dust	240	-22	0	-38
2	Wheat dust n°1	270	-2	34	-26
3	Potatoes powder	270	-34	-20	-44
4	Crushed waste dust	Experimental value not determined			
5	Zinc powder	Experimental value not determined			
6	Cacao powder	240	-20	-4	-34
7	Wood and flax dust	300	-34	-14	-48
8	Activated carbon dust	> 450	Values not calculable		
9	Wheat dust n°2	290	-30	-10	-46
10	White wood dust	Experimental value not determined			
11	Wood with asphalt dust	Experimental value not determined			
12	Wheat dust n°3	Experimental value not determined			
13	Persulphate powder	Experimental value not determined			
14	Coal dust	362	-106	-70	-128

Values are not calculable when experimental temperature is higher than 450 °C. Coloration represent the accuracy of correlation obtained: the more darkly, the less accurate correlation.

7.3. Synthesis

Principal lessons resulting from this study are summarised below.

For 5-mm dust layers, it is possible to determinate a theoretical self-ignition temperature based on self-ignition tests in heating ovens. The most adapted Biot number (α) seems equal to 1, it corresponds to a repartition of heat transfer between conduction inside the layer and convection on the surface (Thomas and Bowes's model). In these conditions, the uncertainty obtained for self-ignition temperature is less than 30 K, except zinc powder

(150 K) and wheat dust no. 1 (80 K). It must be pointed out that calculated values are generally higher than experimental ones.

For 12.5 and 15 mm dust layer thickness, determination of a theoretical self-ignition temperature based on self-ignition tests in heating ovens is also possible, if the chosen Biot number (α) tends to infinite. This condition corresponds to the limitation of heat transfer by conduction inside the dust layer (Frank-Kamenetskii's model). For these conditions, the uncertainty on self-ignition temperature is about 10–30 K, except for wheat dust no. 2 (98 K) and coal dust (70 K).

Table 5
Relative differences between theoretical self-ignition temperature values for several α values

Ref.	Samples	Difference between theoretical self-ignition temperature values in K (relative difference in %)					
		Between $\alpha = 1$ and infinite			Between $\alpha = 1/2$ and infinite		
		5 mm	12.5 mm	15 mm	5 mm	12.5 mm	15 mm
1	Purifying station mud dust	-28 (-4.8)	-22 (-4.2)	-22 (-4.3)	-46 (-7.9)	-38 (-7.3)	-38 (-7.4)
2	Wheat dust no. 1	-53 (-7.5)	-38 (-6.4)	-36 (-6.2)	-87 (-12.3)	-64 (-10.8)	-60 (-10.4)
3	Potatoes powder	-16 (-2.8)	-16 (-3.0)	-14 (-2.7)	-30 (-5.3)	-26 (-4.9)	-24 (-4.6)
4	Crushed waste dust	-18 (-3.2)	-14 (-2.6)	-16 (-3.0)	-30 (-5.3)	-25 (-4.7)	-26 (-5.0)
5	Zinc powder	-24 (-3.3)	-22 (-3.3)	-22 (-3.3)	-40 (-5.5)	-36 (-5.4)	-38 (-5.7)
6	Cacao powder	-20 (-3.6)	-18 (-3.5)	-16 (-3.1)	-34 (-6.0)	-30 (-5.8)	-30 (-5.9)
7	Wood and flax dust	-22 (-3.6)	-20 (-3.5)	-20 (-3.6)	-40 (6.5)	-34 (-6.0)	-34 (-6.1)
8	Activated carbon dust	-104 (-10.1)	-66 (-8.1)	-62 (-7.9)	-170 (-16.5)	-112 (-13.7)	-102 (-13.0)
9	Wheat dust no. 2	-28 (-4.5)	-24 (-4.2)	-20 (-3.6)	-46 (-7.4)	-38 (-6.7)	-36 (-6.5)
10	White wood dust	-26 (-4.1)	-22 (-3.8)	-20 (-3.5)	-46 (7.2)	-36 (-6.2)	-36 (-6.3)
11	Wood with asphalt dust	-26 (-4.2)	-22 (-3.9)	-20 (-3.6)	-46 (-7.4)	-38 (-6.7)	-36 (-6.5)
12	Wheat dust no. 3	-26 (-4.2)	-20 (-3.5)	-20 (-3.6)	-38 (-6.1)	-36 (-6.4)	-36 (-6.5)
13	Persulphate powder	-20 (-4.0)	-18 (-4.0)	-18 (-4.1)	-36 (-7.2)	-30 (-6.7)	-30 (-6.8)
14	Coal dust	-52 (-7.5)	-38 (-6.5)	-36 (6.4)	-84 (-12.2)	-62 (-10.6)	-58 (-10.3)
Average (all values included)		-33.1 (-4.8)	-25.7 (-4.3)	-24.4 (-4.2)	-55.2 (-8.1)	-43.2 (-7.3)	-41.7 (-7.2)
Standard deviation (all values included)		23.3 (2.1)	13.6 (1.5)	12.7 (1.5)	37.4 (3.3)	22.9 (2.6)	20.2 (2.4)

This study has also shown that for several tested samples (e.g. zinc, wheat or coal dust), there is a discrepancy between theoretical value of self-ignition temperature and the experimental ones. Different explanations can be found:

- the most adapted α value can be lower than 1/2. This is probably true for zinc dust. In fact, a study carried out by INERIS [13] showed that Frank-Kamenetskii's model is not applicable to aluminum dust, due to good conduction efficiency. A complementary study is necessary to extend this hypothesis to other samples characterised by a high conduction coefficient, such as metal powders in specific granulometry conditions,
- samples chemical modification at low temperature, such as complex agro-alimentary molecules. This could explain the poor correlation obtained for, e.g. wheat dust,
- in the case of persulphate powder, a foaming was observed. This particular behaviour can also be one of the causes of a bad correlation.

In all these hypothesis, equations from Frank-Kamenetskii's model, which was used in the study, are not valid.

8. Conclusion

The correlation method describes in this paper can be considered valid to estimate self-ignition temperature of a dust layer for several samples from the results of self-ignition tests in ovens, if the value of Biot number (α) is judiciously chosen:

- for 5-mm dust layers, the most adapted value is equal to 1,
- for 12.5 and 15 mm dust layers, it is preferable to choose a very high value for α .

Uncertainty on results is lower than 30 %, if temperature is calculated in Kelvin. It is in the same order than uncertainty induced by testing a 15 mm layer self-ignition temperature, which is less difficult to obtain but pessimistic, instead of a 5 mm layer self-ignition temperature.

Finally, when the sample behaviour (foaming ...) does not allows to carry out the standardised procedure to measure self-ignition temperature of a 5 mm dust layer, we recommend:

- to calculate the theoretical self-ignition temperature based on results of self-ignition tests in heating ovens, within the validity domain of Frank-Kamenetskii's model,

- to consider the self-ignition temperature of a 15 mm thick sample, determined by the standardised method, in other situations.

In both cases, uncertainties on results must be taken into account.

Additional tests would help refine the knowledge of samples for which Frank-Kamenetskii's model is not valid, e.g. materials whose conduction coefficient is very high or samples which undergo chemical conversion at low temperatures.

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