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Determination of the Smouldering Temperature on the Basis of Adiabatic Tests

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Bulk goods are widely employed in different industrial sectors comprising the food, mining and process industry. When handling bulk goods, deposits on hot surfaces, like pipe or heat exchangers often cannot be completely excluded. These deposits can start to smoulder and could be sources of fire or an explosion. This is a problem not to be underrated which brings many safety issues for the industry and the process engineers. Based on this topic, a simulation was created to determine the smolder temperature under different ambient conditions. This simulation is based on the theory of Frank-Kamenetzki (1959) and Thomas (Bowes, 1984), which describes the beginning of a combustion process through an imbalance of heat production and heat dissipation. This simulation should be a supplement of the determination of the smolder temperature, described in DIN EN 50281-2-1 and can simplify the risk assessment of dust layers on hot surfaces.

1. Introduction

In this paper, the ignition of a dust layer on a hot surface is theoretically solved with the help of the theories of Frank-Kamenetzki and Thomas. This model, provided that the kinetic and thermal parameters are known, creates a solution for any material and makes a prediction about the ignition temperature. The calculated ignition temperature will be checked against the measured smolder temperature according to DIN EN 5028-1-2-1 with a 5 mm and 12.5 mm layer thickness. As test items charcoal powder, wheat flour, cocoa powder and cellulose were used.

2. Theoretical Bases of the thermal explosion

To describe the ignition of dust layers, the effects of thermal conductivity and heat production of the substance must be incorporated into the mathematical model. This is done by the Fourier law and the Arrhenius term. Since the ignition point is described as an imbalance of heat production and heat dissipation, the Fourier differential equation and the Arrhenius term are equated, see in Eq(1).

$$\Delta T \cdot \lambda = Q \cdot z \cdot e^{-\frac{E}{R \cdot T}} \quad (1)$$

If Eq(1) is solved for spatial temperature changes ΔT, we get a differential equation that describes the temperature change in the dust bulk Eq(2), provided that a change in temperature is equal to an ignition.

$$\Delta T = \frac{Q}{\lambda} \cdot z \cdot e^{-\frac{E}{R \cdot T}} \quad (2)$$

To solve this differential equation, dimensionless length Eq(3) and dimensionless temperature Eq(4) are imported.

$$\xi = \frac{\chi}{r} \quad (3)$$

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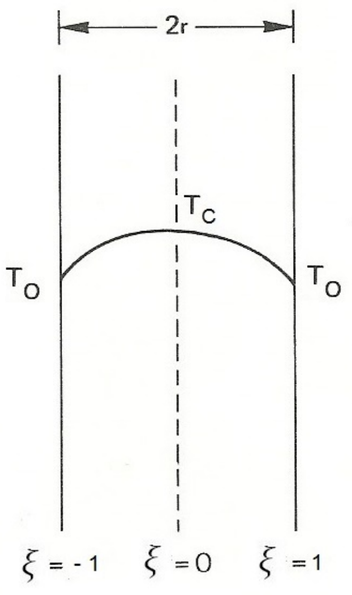

Figure 1: Temperature distribution of a dust body with a fixed storage temperature by Frank-Kamenetzki (Bowes, 1984)

Dimensionless length describes the relation between any position χ in the bulk and the radius r. The dimensionless length can take values between -1 and 1.

$$\Theta = \frac{E}{R \cdot T_O} \cdot \frac{T - T_O}{T_O} \tag{4}$$

The dimensionless temperature (Θ) describes the time dependent temperature change in the bulk resulting from the outside temperature (T_O) and the core temperature of the bulk (T). The core temperature will rise with time and reach a critical point (T_C). The whole description of the body with dimensionless length and temperature is shown in Figure 1. With the two sizes used in Eq(2) an analytical solution based on the similarity theory becomes possible and a dimensionless stationer differential equation of the thermal explosion is found Eq(5).

$$\Delta\xi\Theta = -\frac{Q}{\lambda} \cdot \frac{E}{RT_O^2} \cdot r^2 \cdot z \cdot e^{-\frac{E}{RT_O}} \cdot e^{\Theta} \tag{5}$$

All constant parameters of the differential equation are summarized to the dimensionless parameter δ Eq(6)

$$\delta = -\frac{Q}{\lambda} \cdot \frac{E}{RT_O^2} \cdot r^2 \cdot e^{-\frac{E}{RT_O}} \tag{6}$$

And the dimensionless stationer DE get the final form of Eq(7)

$$\frac{\mathrm{d}^2\Theta}{\mathrm{d}\xi^2} = -\delta \cdot e^{\Theta} \tag{7}$$

Eq(7) shows that the function of the dimensionless temperature is only dependent on δ and ξ. The factors of the ignition can be completely described with parameter δ, which encompasses the geometrical form (r^2), the physical characteristics (Q, λ) and the kinetic behaviour (Arrhenius equation). Thus, a critical parameter $\delta_{crit.}$ for different geometries can be calculated and all temperatures that return a value higher than $\delta_{crit.}$ will induce an ignition. More information about this approach can be found in Frank-Kamenetzki (1959) or Kimpel, Horn (2012).

3. Theoretical Bases of the dust layer

Unlike a geometrical body, a dust layer not only has a fixed storage temperature, but a hot surface on the bottom (T_p) and a colder ambient on top (T_A). This temperature difference leads to a heat flow inside and outside the dust layer. Thereby a second heat resistance exists between the surface of the dust layer and the ambience, see Figure 2, and can be described with the biot number Eq(8).

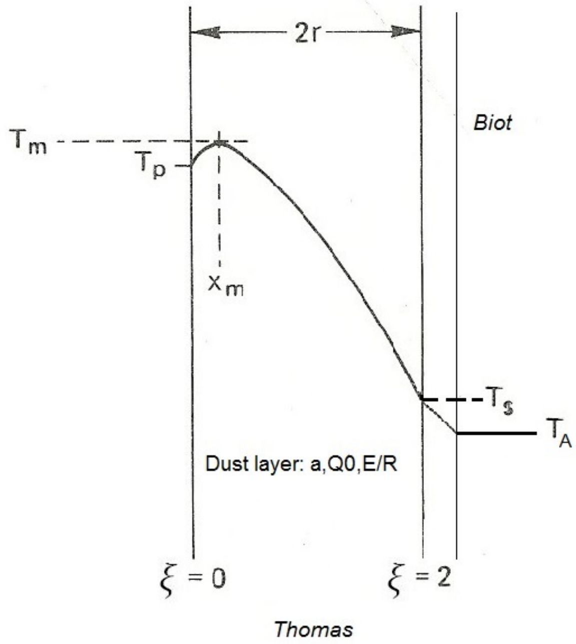

Figure 2: Model of a Dust Layer on a Hot Surface by Thomas (Bowes, 1984)

The biot number is a dimensionless quantity and is the quotient of the heat resistance of the body and the total heat transmission resistance of the air. Therefore, the biot number describes the heat transfer on the surface of the dust. The total heat transmission is consists of the heat radiation and the convection in this case.

$$Bi = \frac{\alpha_{total}}{\lambda_{sample}} \cdot r \quad (8)$$

These terms can be described with the Stefan Boltzmann term and the Rayleigh number, are applied in Eq(8) and result in Eq(9). The exact description can be found in Hensel, John (1991).

$$Bi = \frac{4 \cdot \sigma \cdot T_A^3 + \left(2 + 0{,}6 \cdot Ra^{\frac{1}{4}}\right) \cdot \frac{\lambda_{air}}{d}}{\lambda_{sample}} \cdot \mathrm{r} \quad (9)$$

To solve Eq(7) for dust layers, the new boundary value from Figure 2 with the biot number must be used. The hot plate (T_p) is described as a perfect isolator with the condition Θ = 0 at ξ=0 and conducts no heat.

$$\Theta_A = \frac{E}{RT_p^2}\,(T_A - T_p) \quad (10)$$

At the surface of the dust layer Eq(11) is applied to describe the heat transmission. Θ_A is the dimensionless temperature between the surface and the ambience and is described in Eq(10). The dimensionless length is now 2, because the thickness is the double radius.

$$-\frac{d\Theta}{d\xi} = -Bi \cdot \Theta_A \quad at\ \xi = 2 \quad (11)$$

By inserting this boundary value in Eq(7) we get the Eq(12) for $\delta_{crit.}$, which describes the dust layer on a hot surface. At this point, it can be assumed that the radius is greater than the layer thickness, so the layer radius is infinite and receives one dimensional consideration.

$$\delta_{krit.} \approx \frac{1}{2}\left(\frac{Bi}{1 + 2\,Bi}\right)^2 (1{,}4 - \Theta_A)^2 \quad (12)$$

Now it is possible to calculate $\delta_{crit.}$ and insert it into Eq(6). In this case, T_O turns into T_p and the equation is solved to T_p, resulting in Eq(13). With Eq(13) an iterative solution of the ignition temperature of the dust layer can be calculated with different layer thicknesses and ambient temperatures. The accurate derivation can be found in Bowes (1984)

$$T_p = \frac{1}{\ln(\frac{1}{\delta_{crit.}} \cdot \frac{Q_0}{a} \cdot \frac{E}{R} \cdot \frac{L^2}{T_p^2})} \cdot \frac{E}{R} \tag{13}$$

4. Experimental Investigation

In this chapter the main investigations and the methods are described. The adiabatic heat storage test and the transient plane heat source method to measure the thermal conductivity are time-consuming, but run after a small set up-time by themselves. The results for the individual test items are summarized in the Tables 1 and 2. Additionally, the smolder temperature according to DIN EN 50281-2-1 was determined in order to compare results with the simulation.

4.1 Adiabatic heat storage test

The first step was the adiabatic heat storage test to get the kinetic parameters E/R and Q_0. The test adhered to the method in DIN EN 15188 and was carried out with all test items. The results are summarized in Table 1.

Table 1: Results of the adiabatic heat storage test

Test substance	Activation Energy E [kJ/mol]	Arrhenius Factor Q_0 [K/s]
cellulose	140	$4.6 \cdot 10^{12}$
wheat flour	150	$1.7 \cdot 10^{14}$
cocoa powder	102	$1.9 \cdot 10^{10}$
charcoal powder	64	$1.7 \cdot 10^{05}$

For the test a 400 mL wire basket was filled with the test item and was put in a hot-air convection oven. The test item is at first kept at a specified storage temperature (90 °C) for approx. 24 h. If the core temperature of the test item increases during the storage period due to a self-heating process, then the oven temperature is set to track the sample temperature, this generates a quasi-adiabatic environment. If no self-heating is observed during the storage period, then the oven temperature is increased by 1 K/h up to the point where self-heating is observed, from this point the oven is set to track then sample temperature and create a quasi-adiabatic environment. For the self-heating phase of the test item the data are plotted in a dimensionless form as a function of the time. The gradient of this linear equation is E/R and the axis intercept is Q_0.

4.2 Transient plane heat source method

The second investigation was the transient plane heat source method (Hot Disk), measuring the thermal conductivity, thermal diffusivity and specific heat, according to ISO 22007-2. These thermal parameters are required for describing the temperature change inside the dust bulk. In this method a thin foiled sensor is put into a cylindrical volume (293 cm³, d=h) of the test item. The sensor supplies a selected energy level to the sample over a fixed time period and measures isochronal the temperature change. By plotting the temperature versus time, the temperature expansion can be calculated. The results are shown in Table 2.

Table 2: Results of the transient plane heat source method

	thermal diffusivity [m²/s]	thermal conductivity [W/(m·K)]	specific heat [J/(kg·K)]
cellulose	$9.87 \cdot 10^{-8}$	0.0900	2100
wheat flour	$9.26 \cdot 10^{-8}$	0.1100	1700
cocoa powder	$8.36 \cdot 10^{-8}$	0.0900	2500
charcoal powder	$25.5 \cdot 10^{-8}$	0.1300	1500

4.3 Smouldering temperature

The determination of the minimum ignition temperature of a dust layer (smouldering temperature) is carried out according to DIN EN 50281-2-1 (Method A) on a hot surface. The hot plate used has a diameter of 200 mm, on which a metal ring with a defined height can be placed. Variation of the ring height allows the investigation of different layer thicknesses of the test item. In this case, 5 mm and 12.5 mm ring heights were used. The temperature of the hot plate temperature is measured via a thermocouple. The temperature of the dust layer is checked by a thermocouple positioned in the centre of the dust layer about 2-3 mm above the hot plate surface. A visible flame or glowing, a temperature over 450 °C in the dust layer, or a temperature of 250 °C above the temperature of the hotplate are considered ignitions. If an ignition is observed, the lowest temperature at which the self-ignition has been observed is rounded down to the next integer of 10 and is noted as the smoulder temperature. An exemplary record of a test with charcoal is shown in Figure 3.

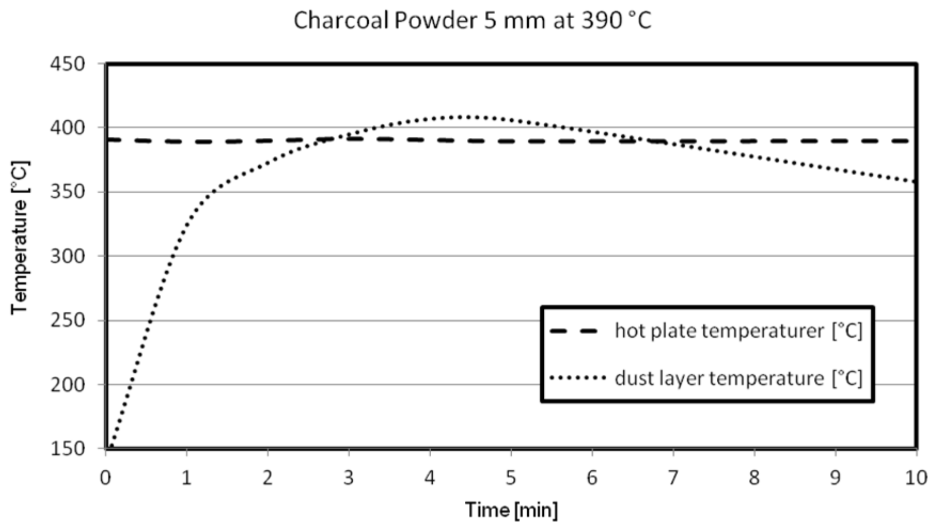

Figure 3: Temperature record of a smouldering test of charcoal 5 mm at 390 °C (ignition)

5. Comparison of the smouldering temperature and the theoretical ignition

The comparison of the measured and calculated smouldering temperatures is shown in Table 3 for the 5 mm dust layer and for the 12.5 mm dust layer in Table 4 with an ambiance temperature of 20 °C.

Table 3: Results of the 5 mm dust layer at ambient temperature

	Measured smouldering temperature [°C]	Calculated ignition temperature [°C]	Deviation [%]
cellulose	345	318	7.8
wheat flour	> 400	277	-
cocoa powder	250	238	4.8
charcoal powder	380	382	0.7

Table 3: Results of the 12.5 mm dust layer at ambient temperature

	Measured smouldering temperature [°C]	Calculated ignition temperature [°C]	Deviation [%]
cellulose	300	305	1.6
wheat flour	270	277	2.5
cocoa powder	210	222	6.0
charcoal powder	360	357	0.9

The results of the calculated ignition temperature match well with the measured smouldering temperature. There is a maximum deviation of about 8 %. Only the 5 mm wheat flour has a smouldering temperature much higher than the calculated ignition temperature. The problem was that the wheat flour had dried up and the dust layer had burst. Thus, in the 5 mm test, the wheat flour did not comply with the mathematical model of the perfect and endless dust layer. The 12.5 mm showed a different behaviour. The thicker layer of the wheat flour did not burst and so additional heat dissipation did not exist. With these requirements, the calculated ignition temperature of the dust layer at 12.5 mm is convenient. Also the results lie within the deviation of 10 % as specified in the literature *Bowes (1984).* With this deviation, a higher handling temperature can be generated with the simulation than with the DIN EN 50281-2-1, see Table 3 and Table 4. The specification according to DIN EN 50281-2-1 stipulates a 75 K safety margin of the measured smouldering temperature of a 5 mm layer to determine the maximum surface temperature for the equipment. This conservative temperature is used in the industry. A more realistic prediction can reduce costs, because the handling temperature has effect on residence time of dryers, used pumps or the temperature of a pipes and equipment in the plant.

Table 3: Handling temperature of the 5 mm dust layer

	DIN EN 50281-2-1 with 75 K safety distance	simulation wit 10 % deduction
cellulose	270	286
wheat flour	-	249
cocoa powder	175	214
charcoal powder	305	344

Table 4: Handling temperature of the 12.5 mm dust layer

	DIN EN 50281-2-1 with 75 K safety distance	simulation wit 10 % deduction
cellulose	270	274
wheat flour	-	249
cocoa powder	175	200
charcoal powder	305	321

The second benefit is that layer thickness and ambient temperature can easily be changed with the simulation. With this feature, an ignition temperature of the dust layer can be derived for individual situations. This is important, because a higher ambient temperature boosts the heat accumulation inside the dust layer, shown in Figure 4. This effect yields a lowering of the ignition temperature. With the smouldering temperature this effect cannot be estimated, since the measurement takes place only at ambient temperature. Also the effect of the smouldering temperature by higher layer thickness can be predicted with the simulation. The common practise according to DIN 57 165 / VDE 165 is that a further reduction of the smouldering temperature is realised by dust layers greater than 5 mm. The reduction is not specified yet. Thus, with the smouldering temperature of a dust layer a flexible contemplation of an industrial plant is very difficult, because many factors are not included. This simulation thus can close this safety gap and provide a tool for precise and easier handling of the self-ignition of dust on a hot surface.

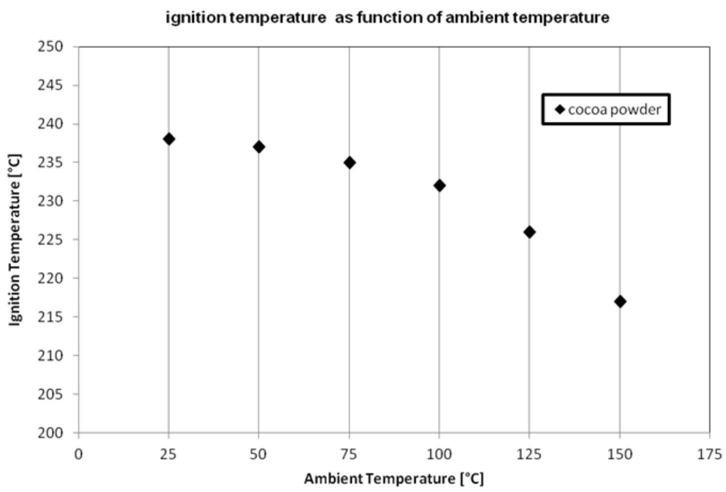

Figure 4: Ignition temperature of cocoa powder as function of ambient temperature

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