The Spontaneous Ignition of Dust Deposits[†] — Ignition Temperature and Induction Time —

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Abstract

The temperature distribution in the combustible dust deposits placed in hot environments is described by a differential equation according to the thermal theory. The temperature profiles of the dust deposits at any time could be calculated at various ambient temperatures by solving the equation using the finite element method. Thus, the minimum ambient temperature for ignition, which is defined as the ignition temperature, and the induction time to ignition could be determined. With the cylindrical cork dust deposits, the resulting temperature distribution in the radial direction at any time, and the self-ignition temperature as well as the induction time to ignition, by varying the size of the deposit, agree well with the experimental data reported by Leuschke, except at extremely high ambient temperatures. Therefore, it is practicable to estimate the spontaneous ignition behavior of dust deposits by computer simulation.

1. Introduction

If the ambient temperature is sufficiently high and the storage time is sufficiently long, combustible dust deposits may spontaneously ignite. Since such spontaneous ignition may result in an explosion causing extreme damage, it is important to reveal the mechanism of spontaneous ignition and to find safety measures to prevent it.

Many studies on the spontaneous ignition of dust deposits have been done, however, most of them are purely theoretical and too difficult for engineers to thoroughly understand, thus they cannot readily be applied. For the above described reasons, Leuschke^{5,6)} has recently reported the results of well-organized and purely experimental studies. The dust used, however, was limited to a specific material, the properties of which were unknown.

Therefore, the results cannot be adequately applied to actual problems.

Using the finite element method, this study analyzes the partial differential equation for heat balance in a cylindrical coordinate system of cork dust deposits; the cork dust being only one specimen in Leuschke's experiments, the properties of which (thermal diffusivity, frequency factor of oxidation rate, activation energy, etc.) are well-known. The study also investigates the possibility of the computer simulation of the spontaneous ignition of dust deposits by comparing the results obtained with variation per time in the temperature distribution of dust deposits, first experimentally established by Leuschke.

2. Bases of the calculation

According to the ignition thermal theory¹⁾, combustible dust deposits have two heat fluxes; one is heat generation caused by the reaction of dust itself, and the other is the heat loss dissipated to the surrounding area. If it can be assumed that the reaction substance loss can be neglected and the reaction rate is in accordance with the zero order equation by Arrhenius

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(during the period of induction time prior to ignition), a rate q of heat evolution per unit volume at an absolute temperature T is given by,

$$q = Qfe^{-E/RT} \quad (1)$$

where Q : heat of reaction [$\text{J} \cdot \text{kg}^{-1}$]
 f : frequency factor of chemical reaction rate [$\text{kg} \cdot \text{m}^{-3} \cdot \text{h}^{-1}$]
 E : activation energy [$\text{J} \cdot \text{mol}^{-1}$]
 R : gas law constant [$\text{J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$]
 q : [$\text{J} \cdot \text{h}^{-1} \cdot \text{m}^{-3}$]

To compare our results to the experimental results of the dust deposits reported by Leuschke, a simulation concerning cylindrical dust deposits was done. Assuming that heat does not flow along the axial direction of the cylindrical dust deposits having a radius R_1 and considering the heat balance of the system, the following differential equation is obtained:

$$\rho C \frac{\partial T}{\partial \theta} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + Qfe^{-E/RT} \quad (2)$$

where r : radial distance in cylindrical coordinates [m]
 ρ : density of the sample [$\text{kg} \cdot \text{m}^{-3}$]
 C : specific heat of the sample [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$]
 θ : storage time [h]
 k : thermal conductivity of the sample [$\text{J} \cdot \text{m}^{-1} \cdot \text{h}^{-1} \cdot \text{K}^{-1}$]

Since this equation has no analytical solution, the finite element method is used to solve the equation with a large-scale computer.

To compare our results to the experimental results reported by Leuschke⁵, Eq. (2) is solved when a cylindrical cork dust deposit is placed under an ambient temperature T_a . In this case, the following initial and boundary conditions are used:

$$\text{I.C. } T(r, 0) = T_r = 293\text{K, at } \theta = 0, \\ 0 \leq r \leq R_1$$

$$\text{B.C. } -k \partial T / \partial r = h (T - T_a), \text{ at } r = R_1, \\ \theta > 0$$

where R_1 : radius of cylinder [m]
 T_r : room temperature [K]
 h : combined heat transfer coefficient of natural convection and radiation from sidewall [$\text{J} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}$]

The following properties are used:

density $\rho = 400 [\text{kg} \cdot \text{m}^{-3}]$
thermal conductivity of cork³⁾
 $k = 0.645T + 158.9 [\text{J} \cdot \text{m}^{-1} \cdot \text{h}^{-1} \cdot \text{K}^{-1}] \quad (3)$
combined heat transfer coefficient of natural convection and radiation from sidewall^{1,2)}
 $h = 1.49 \times 10^4 (\Delta T / \sqrt{\pi} R_1)^{0.25} + 2.04 \times 10^4 \\ \{ (T_a/100)^4 - (T_r/100)^4 \} / (T_a - T_r) \\ [\text{J} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}] \quad (4)$
specific heat of the sample³⁾
 $C = 1.88 \times 10^3 [\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]$
 $Q^{f1)} = 4.6 \times 10^{18} [\text{J} \cdot \text{m}^{-3} \cdot \text{h}^{-1}]$
activation energy
 $E = 9.71 \times 10^4 [\text{J} \cdot \text{mol}^{-1}]$

where T_r : temperature at the external surface of the cylinder $\Delta T = T_a - T_r$

The temperature distribution per time in the cork dust deposits was obtained by solving Eq. (2) using the above conditions, properties, and the finite element method.

3. Comparison between the calculation and experimental results and discussion

3. 1 When the volume of dust deposit is constant

By placing cylindrical cork dust deposits, the diameter and height of which are 0.16 m, in an environment of a specific temperature, Leuschke measured the temperature T_m in the middle of the sample, the temperature T_b near the border of the sample, and the temperature T_h halfway between the middle and border of the sample. He defined the spontaneous ignition temperature as the average of the minimum value of the ambient temperature when the cork dust deposits spontaneously ignite, and the maximum value of the ambient temperature when the deposits do not spontaneously ignite. For instance, the spontaneous ignition temperature of the cork dust deposits having this volume was determined to be around 412 K. The following calculation was carried out based on the experimental conditions. **Figures 1, 2 and 3** show the results of calculation when T_a (ambient temperature) = 408 K, and T_r (room temperature) = 293 K. **Figure 1** shows variations of T_m , T_b , and T_h during the time lapse. **Figures 2 and 3** show the temperature profiles of cork dust deposits after 51 h and 175 h. These figures reveal that the temperature profiles of the cork dust de-

Fig. 1 Heat propagation in cork dust deposit in the lapse of time at $T_a = 408$ K

Fig. 2 Temperature profile of cork dust deposit after 51 h at $T_a = 408$ K

Fig. 3 Temperature profile of cork dust deposit after 175 h at $T_a = 408$ K

posit saturate at a specific level after a certain time lapse, resulting in no spontaneous ignition.

Next, the same equation was calculated for $T_a = 414$ K or 444 K using the same conditions as the experimental conditions used by Leuschke, and the results are shown in Figs. 4 (a) and 5 (a) (for $T_a = 414$ K), and in Figs. 6 (a) and 7 (a) (for $T_a = 444$ K). Figures 4 (a) and 6 (a) reveal that the temperature abruptly rises after a certain time lapse. This temperature rise is defined as the spontaneous ignition start. Figures 4 (a) and 5 (a) (showing the data of $T_a = 414$ K) reveal that the ignition start begins inside the dust deposit as conventionally considered. As shown in Fig. 7 (a), the temperature profile for $T_a = 444$ K totally differs from that of $T_a = 414$ K. Therefore, the simulation results are compared to the experimental results reported by Leuschke in the following description.

Fig. 4(a) Heat propagation in cork dust deposit in the lapse of time at $T_a = 414$ K

Fig. 4(b) The corresponding experimental data to Fig. 4(a) reported by Leuschke at $T_a = 414$ K

Fig. 5(a) Temperature profile of cork dust deposit showing the moment immediate before the ignition at $T_a = 414\text{K}$. Solid line refers to the values after 15.48 h; dashed line refers to the values after 15.49 h

Fig. 5(b) The corresponding experimental data to Fig. 5(a) reported by Leuschke at $T_a = 414\text{K}$

1) Temperature changes with time and the position of the ignition start

Figures 4 (a) and 6 (a) show the heat propagation in the cork dust deposit during the time lapse at $T_a = 414\text{K}$ and 444K . As shown in Fig. 4 (a), when $T_a = 414\text{K}$, the temperature near the border of the sample T_b is initially the highest ($T_b > T_h > T_m$). With the lapse of time, the position of the highest temperature gradually becomes the center of the cylindrical dust deposit. Approximately 15 hours later, the temperature T_m in the middle of the sample

Fig. 6(a) Heat propagation in cork dust deposit in the lapse of time at $T_a = 444\text{K}$

Fig. 6(b) The corresponding experimental data to Fig. 6(a) reported by Leuschke at $T_a = 444\text{K}$

abruptly rises ($T_m > T_h > T_b$), resulting in spontaneous ignition beginning from the center (Fig. 5 (a)). By comparing the results shown in Figs. 4 (a) and 5 (a) to the experimental results reported by Leuschke shown in Figs. 4 (b) and 5 (b), it is revealed that our calculation results satisfactorily agree with the experimental results and their inclination as reported by Leuschke.

On the other hand, when $T_a = 444\text{K}$, the temperature near the border of the sample is significantly high at the earlier stage ($T_b > T_h > T_m$), as shown in Fig. 6 (a). T_m and T_h also gradually rise because of heat conduction, and T_h equals T_b at a certain point (after approximately 4.5 hrs). Following this, however, since the temperature T_h halfway between the middle and the border of the sample is sufficiently high, the reaction in this position is accelerated beyond the activation energy barrier more ra-

Fig. 7(a) Temperature profile of cork dust deposit showing the moment immediate before the ignition at $T_a = 444$ K. Solid line a refers to the values after 5.45 h and b refers to the values after 5.5 h; dashed line refers to the values after 5.51 h

Fig. 7(b) The corresponding experimental data to Fig. 7(a) reported by Leuschke at $T_a = 444$ K

pidly than in the other positions. Moreover, since the thermal conductivity is small, T_h abruptly increases ($T_h > T_m > T_b$). As a result, spontaneous ignition occurs at the point half-way between the border and center of the sample (Fig. 7 (a)). By comparing Figs. 6 (a) and 7 (a) to Figs. 6 (b) and 7 (b), respectively, it is found that the calculation results compare satisfactorily with the experimental results reported by Leuschke. These results are the first reported in this field. In addition, it is very interesting that these results can be explained by the calculation of an equation as simple as Eq. (2).

When the ambient temperature is high

Fig. 8(a) Temperature profile of cork dust deposit showing the moment immediate before the ignition at $T_a = 501$ K. Solid line refers to the values after 1.08 h; dashed line refers to the values after 1.086 h

enough (for instance, at $T_a = 501$ K), appropriate simulation was not obtained for the reasons described below. However, the results of the calculation shown in Fig. 8(a) suggest some pertinent information. When $T_a = 501$ K, the external surface of the cylindrical dust deposit is heated by the surrounding air, and its temperature rises high enough to accelerate the reaction. In addition, the thermal conductivity is very low. As a result, spontaneous ignition occurs at a position adjacent to the external surface. In this case, a very large value of $h =$

Fig. 8(b) The corresponding experimental data to Fig. 8(a) reported by Leuschke at $T_a = 501$ K

$1.67 \times 10^6 \text{ J} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}$ was used so that the induction time would coincide with the measured value. However, the inclination of the graphs was independent of the h values used. Comparing Fig. 8 (a) to (b) reveals that this inclination is similar to the inclination in the experimental results reported by Leuschke.

2) Induction time to ignition

The time that elapsed from when the deposit was placed in an environment the temperature of which is T_a to the time when spontaneous ignition occurred is defined as induction time θ_i . The induction time 15.4 h at ambient temperature $T_a = 414\text{K}$ is read from Fig. 4 (a), and 5.5 h at $T_a = 444\text{K}$ is from Fig. 6 (a). By comparing these values to those shown in Figs. 4 (b) and 6 (b), it is found that θ_i obtained by this method of calculation coincides approximately with that reported by Leuschke.

Simulation for the case when $T_a = 501\text{K}$ is carried out using the combined heat transfer coefficient obtained by Eq. (4). Since the obtained induction time is longer than that reported by Leuschke ($\theta_i \approx 0.7\text{h}$), values of the combined heat transfer coefficient (up to $1.67 \times 10^6 \text{ J} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}$), larger than the h value obtained by Eq. (4), are used to recalculate the induction time. It was impossible to obtain a calculation value of the induction time equivalent to the experimental value by only increasing the h value. The most difficult problem is that under the calculation conditions used in this report, if T_a is higher than the ignition temperature by 100 K, the time period required for the temperature at the circumferential surface of the sample to reach a predetermined temperature of T_a is longer than that of the experimental data reported by Leuschke. This is in spite of extreme enlargement of the h value. Therefore, simulating a case using a relatively high ambient temperature is considered to be impossible at this stage. However, it was found that the temperature profiles at the moment immediately proceeding the ignition had the same inclination irrespective of the h values when $T_a = 501\text{K}$. Therefore, the qualitative explanation shown in Fig. 8 (a) is applicable where the ambient temperature is relatively high.

The above calculation results show that

when the ambient temperature $T_a = 408\text{K}$, spontaneous ignition does not occur; however, if T_a rises to 414 K or higher, spontaneous ignition occurs. These calculation results satisfactorily agree with the experimental results. Therefore, a critical temperature T_{si} (self-ignition temperature) is considered to exist between 408 K and 414 K. When $T_a < T_{si}$, spontaneous ignition does not occur, but if $T_a > T_{si}$, spontaneous ignition does. This T_{si} is defined as the self-ignition temperature in this study, the same as in the report by Leuschke. Hereafter, the self-ignition temperature T_{si} and the induction time θ_i are used as operational variables that directly suppress the danger of spontaneous ignition.

3. 2 Scaled-up dust deposits

1) Dependency of the self-ignition temperature on the dust deposit volume

The self-ignition temperature T_{si} was obtained by varying the volume of dust deposit from $5.0 \times 10^{-5} \text{ m}^3$ (radius $R_1 = 0.02 \text{ m}$) to 10 m^3 (radius $R_1 = 1.17 \text{ m}$). Figure 9 shows the relationship between the obtained self-ignition temperature and the dust volume. In this figure, the closed circles are experimental values reported by Leuschke⁶⁾ and obtained by using cork dust deposits, and the open circles are the values simulated by the authors. The solid line expresses the simulated values. The simulated values satisfactorily coincide with the experimental values in a wide range of volumes.

2) Dependency of induction time on the dust deposit volume

Fig. 9 Dependency of self-ignition temperature upon the cork dust volume

Fig. 10 The induction time to ignition simulated at different overtemperatures as a function of the cork dust volume

To compare our results to the experimental values reported by Leuschke, the difference ($T_a - T_{si}$) is defined as an overtemperature ΔT_o ⁴⁾. The variation in the induction time θ_i at a constant ΔT_o is calculated by varying the dust deposit volume. **Figure 10** illustrates the results obtained. Since the relationship between the induction time and dust deposit volume is linear on a double logarithm graph, θ_i is in proportion to a certain power of the dust deposit volume at a specific overtemperature ΔT_o . On the other hand, Leuschke experimentally obtained the relationship between the dust deposit volume and θ_i not only for cork dust but also for tobacco dust at a constant ΔT_o . Since the experimental data for the cork dust is not disclosed in the report, the experimental data on tobacco dust is shown in **Fig.**

Fig. 11 The experimental induction time to ignition reported by Leuschke at different overtemperatures as a function of the tobacco dust volume

11. (Leuschke reported that the results obtained for the cork dust deposit had an inclination similar to the results obtained for the tobacco dust deposit.) Therefore, our simulation results cannot be directly compared to the experimental data reported by Leuschke, however, these figures show similar inclinations.

4. Conclusions

The above described method of calculation can determine the self-ignition temperature with an approximate accuracy, except for cases where the ambient temperature is extremely high. If possible, it would be desirable to obtain T_{si} using an equation. The temperature profile is not stationary during the initial state but finally reaches a steady state, as shown in **Fig. 1**. It is necessary to discuss whether or not T_{si} is equal to T_a , obtained by replacing the left side of Eq. (2) with zero and by solving the quadratic ordinary differential equation.

The concept used in this study for the balance between heat generation and dissipation is basically the same as the stability criteria for the reaction apparatus. However, most studies on the criteria handle primary reactions as a perfectly mixed system. The analysis used in this study differs from those with respect to the method of analysis and its purposes.

As described above, the results obtained by our method of calculation satisfactorily agree with the results of the experimental data reported by Leuschke, thus suggesting that simulation of the spontaneous ignition of dust deposits is possible.

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Nomenclature

C	: specific heat of the sample	$[\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}]$
E	: activation energy	$[\text{J} \cdot \text{mol}^{-1}]$
f	: frequency factor of chemical reaction rate	$[\text{kg} \cdot \text{m}^{-3} \cdot \text{h}^{-1}]$
h	: combined heat transfer coefficient	$[\text{J} \cdot \text{h}^{-1} \cdot \text{m}^{-2} \cdot \text{K}^{-1}]$
k	: thermal conductivity of the sample	$[\text{J} \cdot \text{h}^{-1} \cdot \text{m}^{-1} \cdot \text{K}^{-1}]$
Q	: heat of reaction	$[\text{J} \cdot \text{kg}^{-1}]$
q	: rate of heat evolution per unit	

volume	$[J \cdot h^{-1} \cdot m^{-3}]$
R : gas law constant	$[J \cdot K^{-1} \cdot mol^{-1}]$
R_1 : radius of cylinder	[m]
τ : radial distance in cylindrical coordinates	[m]
T : absolute temperature	[K]
T_a : ambient temperature	[K]
T_b : temperature near the border of the sample	[K]
T_h : temperature halfway between the middle and border of the sample	[K]
T_m : temperature in the middle of the sample	[K]
T_r : room temperature	[K]
T_R : temperature at the border of the sample	[K]
T_{si} : self-ignition temperature	[K]
ρ : density of the sample	$[kg \cdot m^{-3}]$
θ : storage time	[h]
θ_i : induction time to ignition	[h]

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Explanation of the cover photograph

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(average particle diameter: 5 μ m)