

*Article*

## Spontaneous Ignition of Bagasse Stockpiles in Thailand: A Fire Safety Concern

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**Abstract.** The sugar industry is confronted with the problem of safe bagasse storage over extended periods. In term of fire safety, there have been many instances that the spontaneous ignition promotes ignition inside a large bagasse stockpile and eventually the spontaneous ignition process develops to a flaming fire. This paper presents a method to determine a safe size for bagasse stockpile from spontaneous ignition. The kinetic parameters for spontaneous ignition of bagasse were estimated based on two methods: the Frank-Kamenetskii method and the crossing point method. The bagasse activation energies experimentally determined were ranged from 89 to 109 kJ/mol. Based on the calculated kinetic parameter values, the bagasse stockpile safe sizes for a sugar factory were estimated in term of graphical solutions. For a fixed surrounding temperature, as the bagasse stockpile radius or length increases, the height of the stockpile that spontaneous ignition does not occur decreases and approaches the asymptotic value as the stockpile radius or length approaches infinity. The graphical solutions showed that a bagasse stockpile with any radius or length stored with height below the asymptotic height for a given surrounding temperature was considered to be safe from spontaneous ignition. Applying the calculated activation energy of 89 kJ/mol, the asymptotic heights for bagasse stockpiles were 10.0 m, 7.8 m, and 6.0 m for surrounding temperatures of 40°C, 45°C and 50°C, respectively.

**Keywords:** Spontaneous ignition, bagasse, fire safety.

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## 1. Introduction

In year 2015, Thailand was the worlds' second-largest sugar exporter, following Brazil. In the 2014/15 crop year, the Thai sugar industry produced approximately 11.3 million metric tons of sugar [1]. In the sugar extraction process, sugarcane is pressed to extract its juice and bagasse, the residue from the extracted sugarcane is produced as a by-process product. The sugar industry is faced with the problem of safe bagasse storage over extended periods. In term of fire safety, there have been many instances that the spontaneous ignition promotes ignition inside a large bagasse stockpile and eventually the spontaneous ignition process develops to a flaming fire, for examples, fires on colossal bagasse stockpiles in sugar factories in Nakhon Sawan province [2] and in Udon Thani province [3].

Spontaneous ignition or spontaneous combustion are terms applied to the process of auto-ignition arising from exothermic process within material itself [4]. The term self-heating is also used to describe the exothermic process leading to the ignition event. Common materials that spontaneous ignition can occur are coal stacks, sawdust piles, grain dust stockpiles, cotton meal stockpiles, haystacks, dry freshly made chipboard stacks, as well as bagasse stockpiles.

Large scale experimental study for spontaneous ignition of bagasse stockpile was performed by Dixon [5]. In his work, various sizes of bagasse stockpiles were employed with the largest stockpile size of 75 m by 25 m and 6 m high. His experimental results showed that for large stockpile, the size and geometry did not significantly affect the spontaneous ignition process. The environmental effects on spontaneous ignition were investigated. These included water effects [6], reduced ambient oxygen volume fraction effects [7], and cooked and uncooked material effects [8]. There were several studies on the spontaneous ignition of coal. The experimental studies for determining the coal kinetic parameter for spontaneous ignition were done by Jones [9, 10]. Numerical simulations for spontaneous ignition and combustion of coal were carried out for two-dimensional setup [11] and three-dimensional setup [12]. These simulations were mainly to investigate the spontaneous ignition with porosity effects.

The objectives of this paper were to determine the kinetic parameters for spontaneous ignition of bagasse and to determine the bagasse stockpile size that is safe from spontaneous ignition for a given surrounding temperature. The methods to determine the kinetic parameters of bagasse were based on two approaches: the Frank-Kamenetskii method and the crossing point method. For the bagasse stockpile safe size, typically, the shape of bagasse stockpile is not a geometric shape, since bagasse is randomly dumped on the field after the sugarcane extraction process. However, in order to obtain mathematical expressions of the stockpile safe size, we shall approximate the stockpile with two geometric shapes: a cylinder and a rectangular box. The solutions for the bagasse stockpile safe size were then presented in term of graphical plots.

## 2. Spontaneous Ignition Theory

Different from flaming ignition such as piloted ignition and auto-ignition which initially arises in the gas phase, spontaneous ignition takes place in the solid-phase. It occurs on the lower bound of ignition temperature [8]. The ignition mechanism depends on self-heating within the material. Therefore, the governing equation can be based on the solid heat conduction equation with a heat generation term as

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T + \dot{Q}''' , \quad (1)$$

where  $\rho$  is density,  $c$  is specific heat capacity,  $k$  is thermal conductivity,  $T$  is temperature,  $t$  is time, and  $\dot{Q}'''$  is heat release rate per unit volume.

Term  $\dot{Q}'''$ , heat release rate per unit volume, is due to the exothermic chemical reactions or biological processes within the material. If we assume the porosity of fuel (i.e. bagasse) is high so that oxygen can easily diffuse from surrounding to react with fuel inside the material matrix, then the reaction can be written in term of a zeroth-order Arrhenius rate equation where the reaction rate depends on temperature only. Accordingly,  $\dot{Q}'''$  in Eq. (1) can be written as

$$\dot{Q}''' = A.e^{\frac{-E}{\bar{R}T}} \Delta h_c, \quad (2)$$

where  $A$  is the pre-exponential factor,  $E$  is the activation energy,  $\Delta h_c$  is the fuel heat of combustion, and  $\bar{R}$  is the universal gas constant (8.314 J/mol.K).

The unit of  $\dot{Q}'''$  is kW/m<sup>3</sup>, and the unit of  $\Delta h_c$  is kJ/kg. Therefore the unit of the pre-exponential factor  $A$  in Eq. (2) shall be kg/s.m<sup>3</sup>. In order to evaluate the likelihood of spontaneous ignition of material, the kinetic parameters of  $E$  and  $A$  must be determined. Generally, this can be done by two methods: the Frank-Kamenetskii method and the crossing point method. This work will present both methods in how to determine the kinetic parameters.

## 2.1. Frank-Kamenetskii Method

An early attempt to solve Eq. (1) for spontaneous ignition problem was carried out by Frank-Kamenetskii [13]. The method assumed that self-heating to spontaneous ignition can be predicted based on the existence of the solutions to the system's steady energy equation. Thus the steady state equation of Eq. (1) is

$$k\nabla^2 T + \dot{Q}''' = 0. \quad (3)$$

Normalize the spatial coordinate with the system characteristic length  $r_0$ , the nondimensional form of Eq. (3) is

$$\nabla^2 \theta + \delta e^\theta = 0, \quad (4)$$

where  $\theta$  is the nondimensional temperature given as

$$\theta = \frac{E}{RT_\infty} \left( \frac{T - T_\infty}{T_\infty} \right), \quad (5)$$

where  $T_\infty$  is the surrounding temperature.

A dimensionless parameter  $\delta$  which represents the ratio of chemical energy to thermal conduction in Eq. (4) called the Damkohler number is written as

$$\delta = \frac{E}{RT_\infty} \left( \frac{r_0^2 A \Delta h_c e^{\frac{-E}{RT_\infty}}}{kT_\infty} \right). \quad (6)$$

For a given geometry, Eq. (4) is subjected to the centre boundary conditions and the surface boundary condition. The centre boundary condition is given by a symmetry condition as

$$\nabla \theta|_0 = 0, \quad (7)$$

where the subscript 0 stands for the fuel centre.

The surface boundary condition can be written in term of the heat conduction into the fuel matrix which is balanced by the heat convection at the fuel surface,

$$\nabla \theta|_S + Bi\theta_S = 0, \quad (8)$$

where the subscript  $S$  stands for the fuel surface, and  $Bi$  is the Biot number which defines as

$$Bi = \frac{hr_0}{k} \quad (9)$$

where  $h$  is the convective heat transfer coefficient and  $r_0$  is the system characteristic length.

In the case where the heat transfer coefficient is very high,  $Bi \rightarrow \infty$ , then the boundary condition Eq. (8) reduces to

$$\theta_s = 0 \quad (10)$$

There is a maximum value for  $\delta$  for which a solution of Eq. (4) exists,  $\delta_C$ , which is known as the critical Damkohler number. The critical Damkohler number  $\delta_C$  is principally a function of geometric shape of the solid and the Biot number. Beever [14] gave an excellent review of the critical Damkohler numbers for various geometries and the corrections required for proper application.

In the experimental implementation of the Frank Kamenetskii method, Eq. (6) in term of the critical Damkohler number  $\delta_C$  is rearranged as

$$\ln\left(\frac{\delta_C T_{\infty,ig}^2}{r_0}\right) = -\left(\frac{E}{\bar{R}}\right)\frac{1}{T_{\infty,ig}} + \ln\left(\left(\frac{E}{\bar{R}}\right)\left(\frac{A\Delta h_C}{k}\right)\right) = m_1\left(\frac{1}{T_{\infty,ig}}\right) + C_1, \quad (11)$$

where  $T_{\infty,ig}$  is the critical surrounding temperature (the ignition temperature) that spontaneous ignition can occur for a given geometric shape,  $m_1$  is a slope of the linear plot for the Frank Kamenetskii method, and  $C_1$  is a y-axis interception of the linear plot.

Plotting  $\ln\left(\frac{\delta_C T_{\infty,C}^2}{r_0}\right)$  versus  $1/T_{\infty,ig}$  allows the value of  $E/\bar{R}$  to be determined from the slope  $m_1$  of the linear plot. The value of  $A\Delta h_C/k$  can then be obtained from the y-axis interception, where  $C_1 = \ln\left(\left(\frac{E}{\bar{R}}\right)\left(\frac{A\Delta h_C}{k}\right)\right)$ .

Various tests were conducted in a convective oven on varying sizes of samples, for this work a cube of width  $2r_0$ , to determine  $T_{\infty,ig}$ , for each size. Each experiment consists of placing the prepared samples into a preheated isothermal oven. If the sample centre temperature  $T_0$  exhibits thermal runaway (spontaneous ignition), the surrounding (oven) temperature for that size is lower, until the lowest oven temperature that spontaneous ignition can occur is found and this temperature is defined as  $T_{\infty,ig}$  for that sample size. Finally, knowing  $\delta_C$ ,  $m_1$ , and  $C_1$ , Eq. (11) can be used to predict critical temperatures as a function of size for the material under interest. In practice, the Frank Kamenetskii method can become cumbersome because of the lengthy experimental iteration process to determine  $m_1$  and  $C_1$ . In addition, large amounts of material required, and as the critical condition is approached, the times to spontaneous ignition to occur become lengthy.

## 2.2. Crossing Point Method

To avoid lengthy iteration in determining  $T_{\infty,ig}$ , Chen *et al.* [15, 16] and Jones *et al.* [9, 10] introduced an alternative approach for evaluation of the chemical kinetic parameters governing spontaneous ignition. Their approach was known as the crossing point method. Instead of finding a critical temperature for each sample size, as required by the Frank Kamenetskii method, a crossing point between temperatures is sought. At the crossing point, for Jones approach, the oven temperature is the same as the sample centre temperature and for Chen approach, the sample centre temperature is the same as the sample surface

temperature. This means in both Jones and Chen approaches the temperature gradient ( $\nabla T$ ) in the heat conduction equation (Eq. 1) disappears and the heat conduction equation reduces to

$$\rho c \left. \frac{\partial T}{\partial t} \right|_{CP} = \dot{Q}^m = A e^{\frac{-E}{RT_{CP}}} \Delta h_C \quad (12)$$

where the subscript  $CP$  stands for the crossing point.

Rearrange Eq. (12) as

$$\ln \left( \left. \frac{\partial T}{\partial t} \right|_{CP} \right) = - \left( \frac{E}{\bar{R}} \right) \frac{1}{T_{CP}} + \ln \left( \frac{A \Delta h_C}{\rho c} \right) = m_2 \left( \frac{1}{T_{CP}} \right) + C_2 \quad (13)$$

where  $T_{CP}$  is the crossing point temperature,  $m_2$  is a slope of the linear plot for the crossing point method, and  $C_2$  is a y-axis interception of the linear plot.

A plot of  $\ln \left( \left. \frac{\partial T}{\partial t} \right|_{CP} \right)$  versus  $1/T_{CP}$  yields a straight line whose slope,  $m_2 = -E/\bar{R}$ , gives the

activation energy and whose y-axis interception,  $C_2 = \ln \left( \frac{A \Delta h_C}{\rho c} \right)$ . The plot of Eq. (13) can be produced by varying the oven temperature or by varying the size of the sample.

The slopes of Eq. (11),  $m_1$ , and Eq. (13),  $m_2$ , are essentially the same, however the y-axis interceptions are different by the value of  $\ln(E/(\bar{R}\alpha))$  (i.e.  $C_1 - C_2 = \ln(E/(\bar{R}\alpha))$ ), where  $\alpha$  is the thermal diffusivity of material (i.e.  $\alpha = k/\rho c$ ).

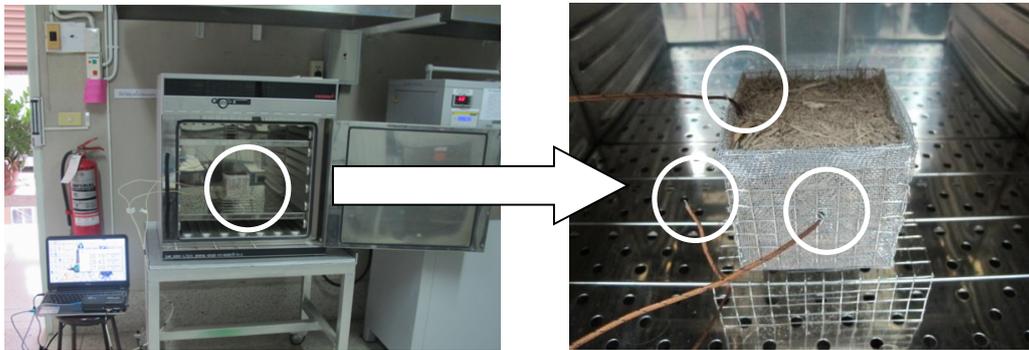
The advantages of the crossing point method over the Frank-Kamenetskii method in determining the kinetic parameters are the followings. First, almost every test results in a data point on the graph, even if the oven temperature is lower than the critical temperature (subcritical temperature) for that sample size. Second, it eliminates the direct Biot number effects on data interpretation. Therefore, the heat transfer coefficient in the oven and the conductivity of the sample need not be known during the experiments. Finally, the critical Damkohler number  $\delta_C$  do not need to be evaluated in the experiment.

### 3. Experimental Setup

The experimental study of spontaneous ignition of bagasse was carried out in a natural convective oven Memmert model UNB 100 as shown in Fig. 1. Three type K thermocouples were installed to continuously measure sample surrounding (oven) temperature, sample surface temperature, and sample centre temperature. Bagasse samples were collected from bagasse stockpile fields and kept in a black plastic bag to preserve the same original condition as they were in the actual stockpile field as much as possible. Three wire mesh cubical baskets with widths of 8, 9 and 10 cm were used in the experiments. In every test, a density of bagasse filled in the basket was kept constant at approximately 1 g/cm<sup>3</sup>. A test started by preheating the oven to a setting temperature. When the oven temperature reached a steady state setting temperature, the oven door was opened, a sample was placed into the oven and then closed the oven door. The surrounding (oven), sample surface, and sample centre temperatures were continuously monitored via a DAQ system with a sampling rate of 1 Hz. Each test was carried out until the sample centre temperature exhibited a thermal runaway, or no sign of ignition was observed after the sample centre temperature reached the oven temperature for at least 2 hours time period.

For the Frank-Kamenetskii method, a sample centre temperature was a main parameter to observe. A test stopped when the sample centre temperature exhibited a thermal runaway (spontaneous ignition). Then the oven temperature was lower and the test was repeated for the same basket size until the lowest oven temperature that spontaneous ignition can occur was found and this oven temperature was defined as the critical surrounding temperature (ignition temperature) for that sample size. At least two tests were repeated at the critical surrounding temperature to ensure the test data repeatability.

For the crossing point method, the crossing point temperatures were determined depending on Jones method [9] or Chen method [15]. For Jones method, the crossing point temperature was defined at the temperature when the sample centre temperature was equal to the surrounding (oven) temperature. For Chen method, the crossing point temperature was defined at the temperature when the sample centre temperature was equal to the sample surface temperature. Every test data could be used to determine the crossing point temperatures even for a test where the oven temperature was lower than the ignition temperature.



Three thermocouples are used to measure the oven and sample temperatures.

Fig 1. Experimental setup for a study of spontaneous ignition of bagasse stockpile.

## 4. Results

### 4.1. General Observation

Temperature evolution with time for a sample basket size of 10 cm at critical and subcritical surrounding temperatures are illustrated in Fig. 2 and Fig. 3, respectively. It should be noted that the oven was preheated to a setting temperature prior to each test, and thus the oven temperature was constant. However, the thermocouple used to measure the oven temperature was placed in its position at the same time when placed the sample into the oven. Therefore the reading temperatures of the oven started from the room temperature as same as the sample surface and its centre. In Fig. 2, at the oven temperature of 190°C, the sample centre temperature increased with time until it crossed with the oven and surface temperatures. The crossing points were indicated with a broken line circle in the figure. After the crossing points, the centre temperature still continued to rise until at approximately 14,000 seconds, a thermal runaway was achieved. The test was repeated by lowering the oven temperature to 187.5°C. At this oven temperature of 187.5°C (see Fig. 3), the sample surface and centre temperatures rose with time until they reached steady state. No sign of spontaneous ignition was found as the centre temperature stayed flat until the test finished. Accordingly, the oven temperature of 190°C was the lowest temperature that the spontaneous ignition could occur. Therefore this temperature was defined as the critical surrounding temperature for a cubical basket size of 10 cm. Although the spontaneous ignition did not occur at the oven temperature of 187.5°C, the crossing points for both Jones and Chen methods still could be determined as indicated by a broken line circle in Fig. 3. The experiments were carried out for a cubical basket of width  $2r_0$  for three sizes (e.g. 8, 9, and 10 cm). The test data for the critical surrounding temperatures, the crossing point temperatures for both Jones and Chen methods are summarized in Table 1.

Figure 4 illustrates sample behaviour at the cubical centre after the tests for the basket size of 10 cm. The left picture depicted the case where the oven temperature was 190°C. After removed bagasse covering on the surface, ignition evidence was noticed. The bagasse at the cubical centre turned black as it became char due to the pyrolysis process. On the right picture of Fig. 4 where the oven temperature was 187.5°C, no evidence of ignition was observed as the bagasse at the centre still looked like a virgin bagasse.

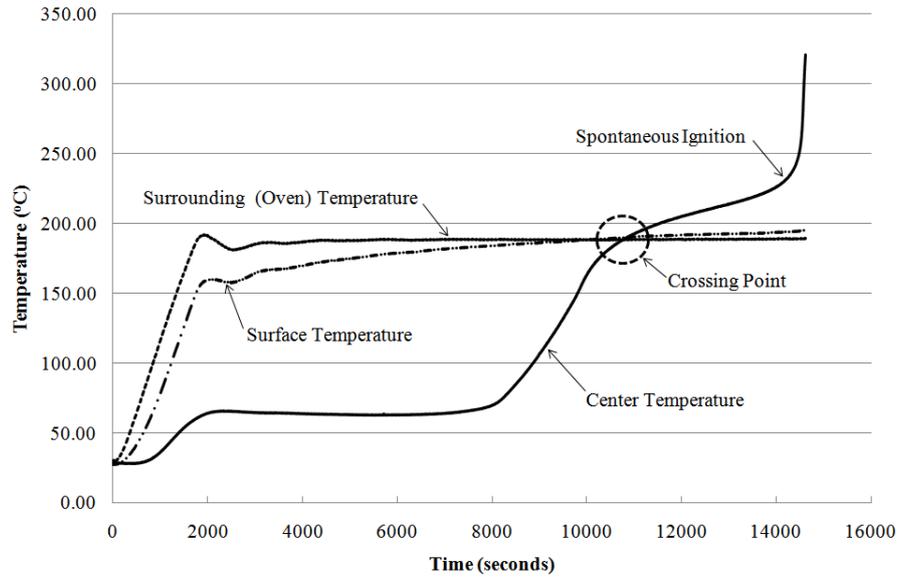


Fig. 2. Temperature evolution with time for a basket size of 10 cm at an oven temperature of 190°C (critical surrounding temperature).

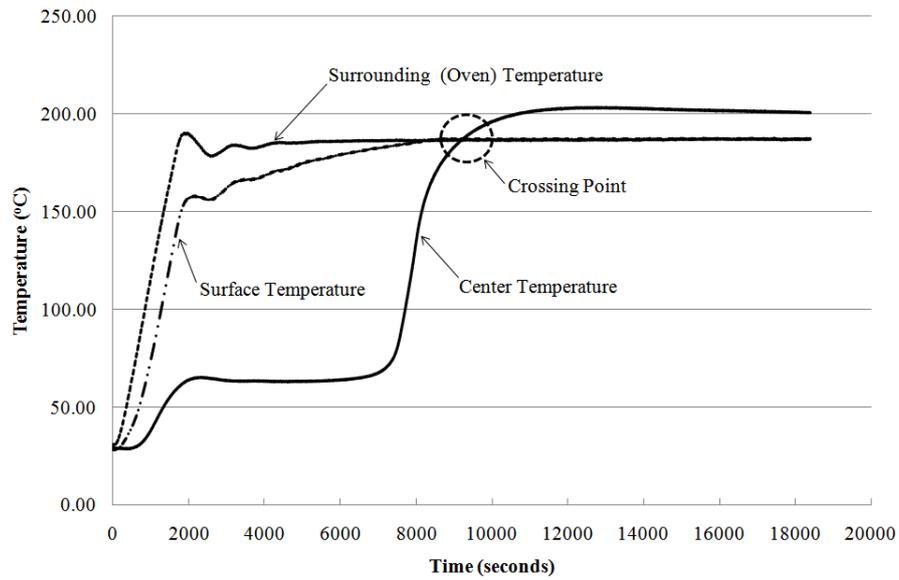


Fig. 3. Temperature evolution with time for a basket size of 10 cm at an oven temperature of 187.5°C (subcritical surrounding temperature).

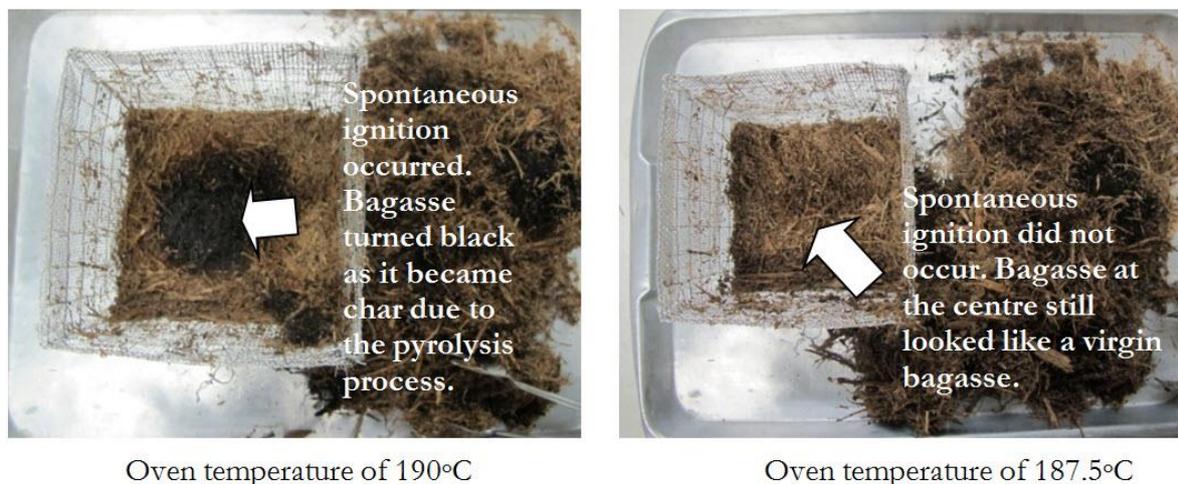


Fig. 4. Pictures of sample centre after the tests for cubical sample basket size of 10 cm.

Table 1. Summary of critical surrounding (oven) temperatures, crossing point temperatures, and slopes at the crossing point of the centre temperature  $((\partial T / \partial t)_{CP})$ .

Sample cubical basket size, $2r_0$ (cm)	Surrounding (oven) temperature ( $^{\circ}\text{C}$ )	Jones method		Chen method		Remark
		$T_{CP}$ ( $^{\circ}\text{C}$ )	$\left(\frac{\partial T}{\partial t}\right)_{CP}$ ( $^{\circ}\text{C}/\text{s}$ )	$T_{CP}$ ( $^{\circ}\text{C}$ )	$\left(\frac{\partial T}{\partial t}\right)_{CP}$ ( $^{\circ}\text{C}/\text{s}$ )	
8	197.5	197	0.027	198	0.023	Not ignite
8	200	201	0.034	201	0.033	Ignite
8	200	200	0.021	200	0.033	Ignite
9	192.5	191	0.019	194	0.018	Not ignite
9	195	194	0.030	196	0.027	Ignite
9	195	194	0.026	196	0.024	Ignite
10	187.5	187	0.016	188	0.015	Not ignite
10	190	189	0.019	191	0.017	Ignite
10	190	189	0.019	190	0.018	Ignite

#### 4.2. Frank-Kamenetskii Method

In previous work in progress [17], the bagasse activation energy based on the Frank-Kamenetskii method has been reported and it is presented again here. Fig. 5 plots a linear line of  $\ln\left(\frac{\delta_c T_{\infty,C}^2}{r_0}\right)$  versus  $1/T_{\infty,ig}$  according to Eq. (11). For a cube of width  $2r_0$ , the critical Damkohler number  $\delta_c$  is 2.52 [14]. The plot relation is extremely linear, with a correlation coefficient ( $R^2$ ) of 0.998. Determining from the slope and y-axis interception, the activation energy of 89 kJ/mol and  $A\Delta h_c/k$  of  $2.22 \times 10^{14}$  K/m<sup>2</sup> were obtained.

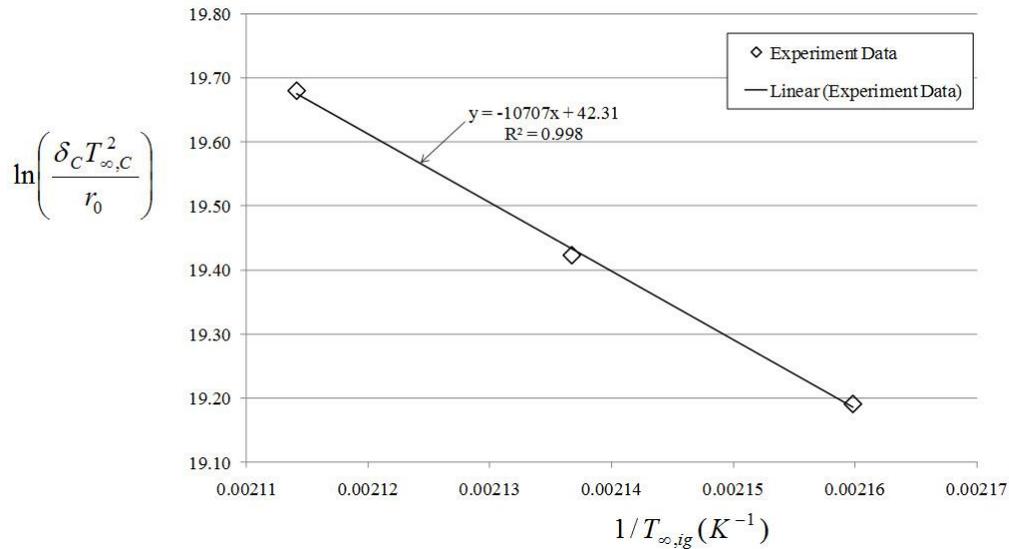


Fig. 5. A linear plot of  $\ln\left(\frac{\delta_C T_{\infty,C}^2}{r_0}\right)$  vs.  $1/T_{\infty,ig}$  for the Frank Kamenetskii method.

### 4.3. Crossing Point Method

A linear plot of  $\ln\left(\frac{\partial T}{\partial t}\bigg|_{CP}\right)$  versus  $1/T_{CP}$  for both Jones and Chen crossing point methods are shown in

Fig. 6 From the slopes of the linear trend lines, the activation energy based on Jones crossing point was 109 kJ/mol, and based on Chen crossing point was 104 kJ/mol. The activation energy values based on both approaches show good agreement within 5 percent difference.

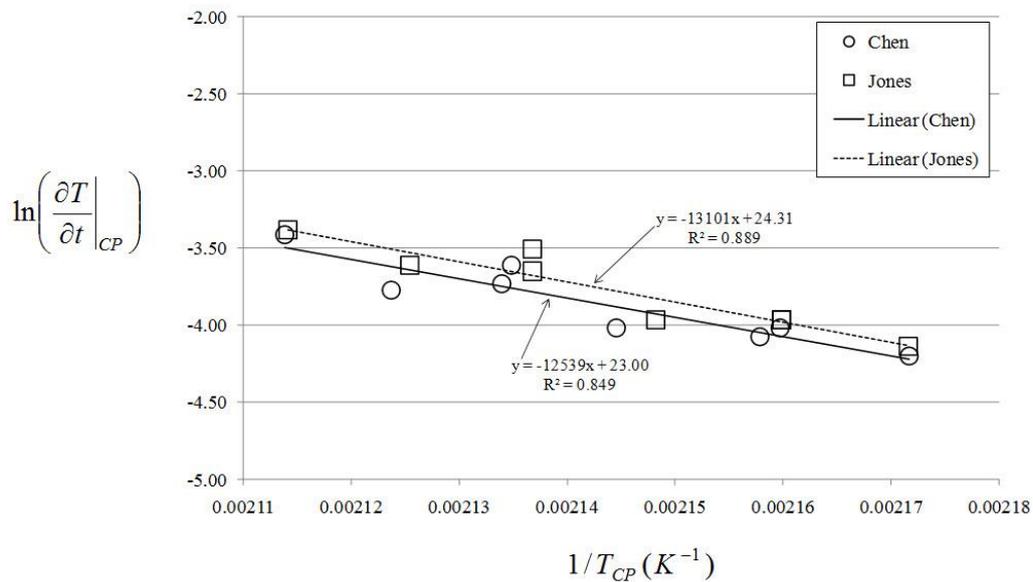


Fig. 6. A linear plot of  $\ln\left(\frac{\partial T}{\partial t}\bigg|_{CP}\right)$  vs.  $1/T_{CP}$  for the crossing point method.

## 5. Discussions

### 5.1. Activation Energy

A survey of bagasse activation energy for various sources compared with this work is presented in Table 2. Nassar *et al.* [18] carried out a series of TGA and DTA experiments for small sample sizes (an initial mass of approximately 18 mg) of bagasse in Egypt and suggested that the pyrolysis process of bagasse could be split into two stages: volatilization stage and decarbonization stage. The activation energy in air was found to be higher than in an inert atmosphere. They reported the bagasse activation energy values of 127.49 kJ/mol for heating in air and 87.90 kJ/mol for heating in Nitrogen. Munir *et al.* [19] reported that the activation energy of sugarcane bagasse was ranging from 58 to 71 kJ/mol for heating in Nitrogen and from 75 to 116 kJ/mol for heating in air. These findings were in good agreement with Nassar *et al.* results. Recent work, from Edreis *et al.* [20] and Edreis and Yao [21] showed that the activation energy values for sugarcane bagasse were ranging from 70.44 to 88.37 kJ/mol for heating in a carbon dioxide atmosphere and from 131.20 to 141.61 kJ/mol for heating in a 75% steam and 25% Nitrogen by volume atmosphere.

The bagasse activation energies determined from this work were 89 kJ/mol (Frank-Kamenetskii method), 109 kJ/mol (Jones crossing point), and 104 kJ/mol (Chen crossing point). The percent difference of activation energy based on the Frank-Kamenetskii method and the crossing point method was approximately 20%. In general, the activation energy values from this work were comparable with the literature values.

Table 2. A survey of activation energy of bagasse.

Heating atmosphere	Activation energy, $E$ (kJ/mol)	References
Air	89	Present work (Frank-Kamenetskii method)
Air	109	Present work (Jones crossing point)
Air	104	Present work (Chen crossing point)
Air	127.49	[18]
Nitrogen	87.90	[18]
Air	75-116	[19]
Nitrogen	58-71	[19]
75% Steam, 25% Nitrogen	131.20-141.61	[21]
Carbon dioxide	70.44-88.37	[20]

### 5.2. Bagasse Stockpile Safe Size

This section is intended to demonstrate how to determine a safe size of bagasse stockpile. Typically, bagasse from the sugar extraction process in a factory is piled up in a non-geometric shape as shown in Fig. 7. In order to estimate the safe size, the bagasse stockpile was assumed to follow two geometric shapes: a cylinder of radius  $r_0$  and height  $2l_0$  and a rectangular box of dimensions  $2a_0 \times 2b_0 \times 2l_0$  (see Fig. 7). The spontaneous ignition is possible to occur when the Damkohler number calculated from Eq. (6) for a given surrounding temperature ( $T_\infty$ ) is greater than the critical Damkohler number ( $\delta_C$ ) for that geometry. Beever [14] reported the critical Damkohler numbers for a cylinder and a rectangular box as the followings:

$$\text{A cylinder:} \quad \delta_C = 2 + 0.841 \left( \frac{r_0}{l_0} \right)^2 \quad (14)$$

$$\text{A rectangular box:} \quad \delta_C = 0.873 \left[ 1 + \left( \frac{l_0}{a_0} \right)^2 + \left( \frac{l_0}{b_0} \right)^2 \right] \quad \text{for } l_0 < a_0, b_0 \quad (15)$$

where  $\delta_c$  is the critical Damkohler number for a given geometry,  $r_0$  is a cylinder radius,  $a_0$  is a half-length of a rectangular box,  $b_0$  is a half-width of a rectangular box, and  $l_0$  is a half-height of a cylinder or a rectangular box.

Equating Eq. (6) with Eq. (14) when approximating a bagasse stockpile shape as a cylinder and Eq. (15) when approximating a bagasse stockpile shape as a rectangular box, and using the activation energy  $E$  of 89 kJ/mol and  $A\Delta h_c/k$  of  $2.22 \times 10^{14}$  K/m<sup>2</sup>, the plots of bagasse stockpile safe sizes for surrounding temperatures of 40°C, 45°C, and 50°C were drawn in Fig. 8 for a cylinder and Fig. 9 for a rectangular box. It should be noted that the maximum surrounding temperature for 64 years period (1951-2014) in Thailand based on a statistical data from Thai meteorological department [22] was approximately 45°C.

The interpretations of Fig. 8 and Fig. 9 are the followings. All the bagasse stockpiles with geometric sizes fall in the area under curve for a given surrounding temperature of Fig. 8 and Fig. 9 are safe from the spontaneous ignition. In contrast, the spontaneous ignition is possible to occur for the bagasse stockpile sizes falling outside the area under curve for that surrounding temperature. As the surrounding temperature increases, the area under curve decreases meaning that the spontaneous ignition is more likely to occur with increasing the surrounding temperature. Increasing the radius  $r_0$  for a cylinder or length  $a_0$  for a rectangular box, the safe size of half-height  $l_0$  decreases. When a cylinder radius or a rectangular box length increases to approach infinity, both geometric shapes approach an infinite slab of half-height  $l_0$ . This confirms that for large stockpile storage, a geometric shape did not affect the spontaneous ignition as experimentally observed by Dixon [5]. For a fixed surrounding temperature, as the radius  $r_0$  or the length  $a_0$  approach infinity (e.g. a bagasse stockpile area is relatively large comparing to its height), the half-height  $l_0$  approaches the asymptotic half-height  $l_{0,\infty}$ . This means that for a bagasse stockpile with any radius or length stored with a half-height  $l_0$  below the asymptotic half-height  $l_{0,\infty}$  for that surrounding temperature is safe from spontaneous ignition.

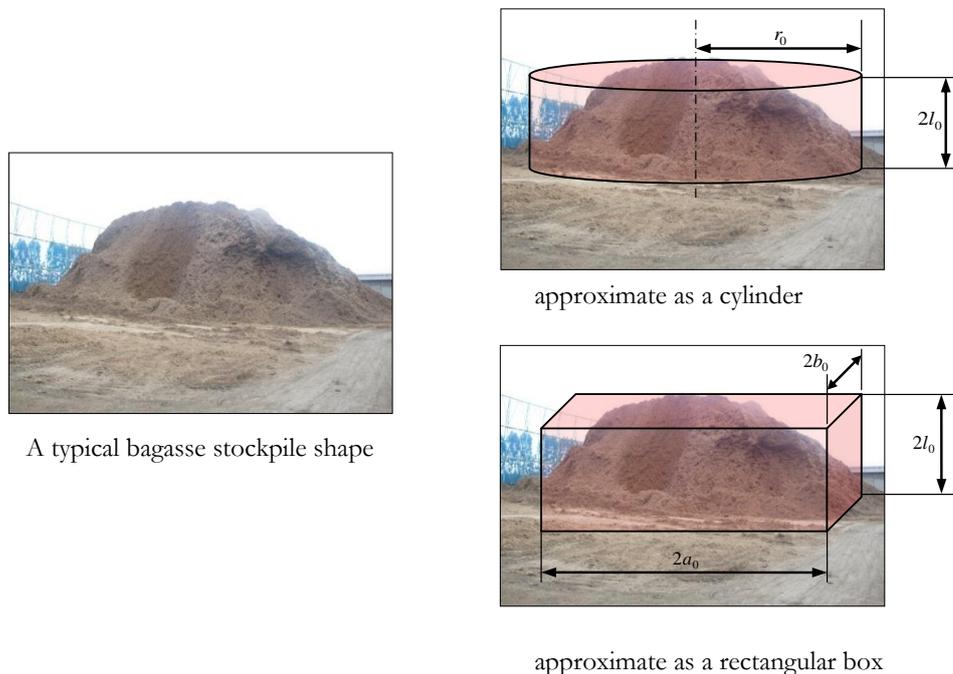


Fig. 7. A typical bagasse stockpile in a sugar factory and its approximation as a geometric shape.

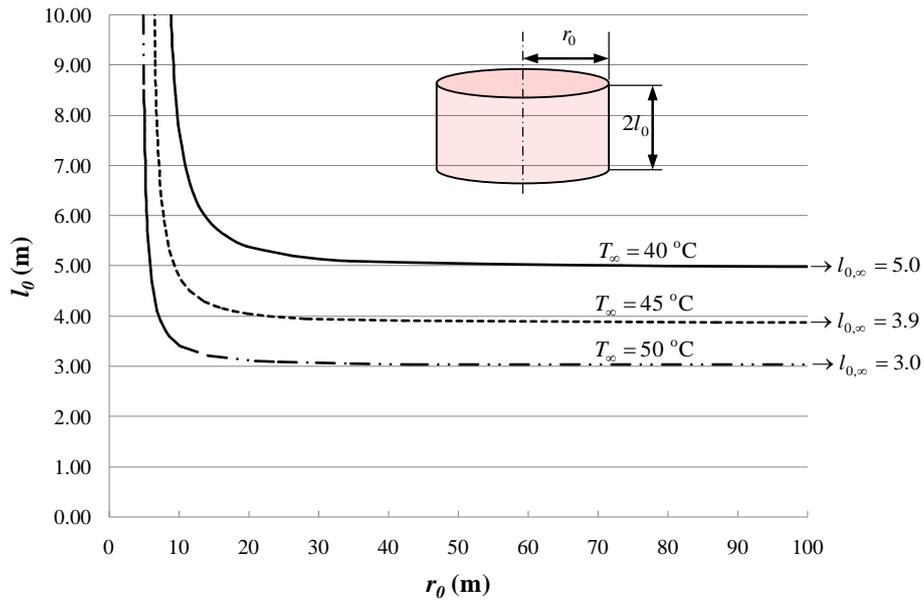


Fig. 8. Safety curve plot based on a cylindrical shape of bagasse stockpile.

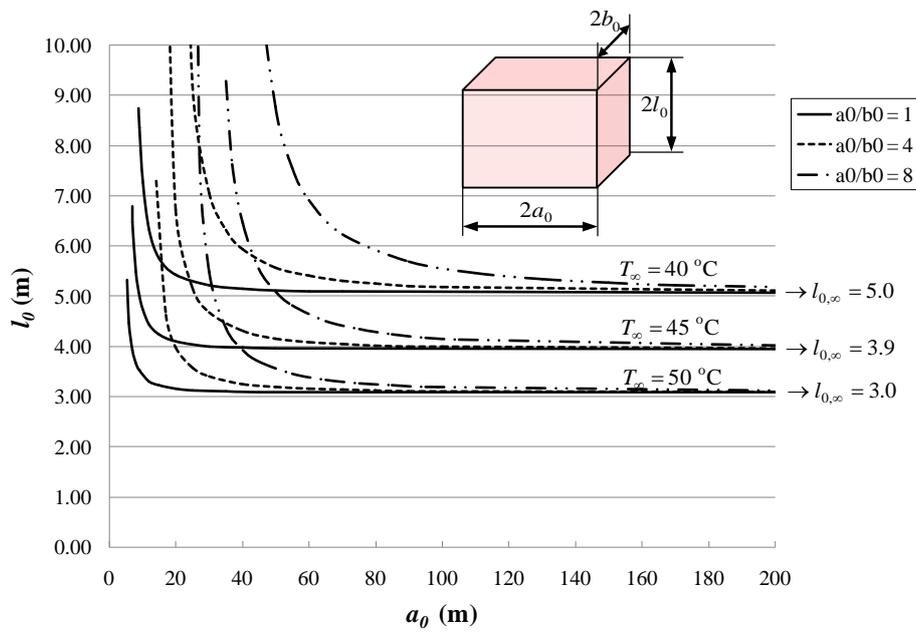


Fig. 9. Safety curve plot based on a rectangular box shape of bagasse stockpile.

Table 3 summarizes the asymptotic half-heights and thus the asymptotic heights for the surrounding temperatures of 40°C, 45°C, and 50°C. In term of a fire safety concern, in order to avoid the risk for spontaneous ignition to occur, Table 3 suggests that a stockpile height should keep below 10.0 m, 7.8 m, and 6.0 m when stored in the surrounding temperatures of 40°C, 45°C, and 50°C, respectively.

Table 3. Asymptotic safe heights for bagasse stockpiles estimated from Fig.8 and Fig.9.

Surrounding temperature, $T_\infty$ (°C)	Asymptotic half-height, $l_{0,\infty}$ (m)	Asymptotic height, $h_{0,\infty} = 2l_{0,\infty}$ (m)
40	5.0	10.0
45	3.9	7.8
50	3.0	6.0

## 6. Conclusion

This paper has presented two methods to determine the kinetic parameters for spontaneous ignition of bagasse, the residue from the sugar extraction process from sugarcane, namely the Frank-Kamenetskii method and the crossing point method. The bagasse activation energy values determined for the experiment were 89 kJ/mol (based on Frank-Kamenetskii method), 104 kJ/mol (based on Chen crossing point method), and 109 kJ/mol (based on Jones crossing point), respectively.

Based on the calculated kinetic parameter values, the bagasse stockpile safe sizes for a sugar factory were determined in term of graphical solutions. For a fixed surrounding temperature, as the bagasse stockpile radius or length increases, the half-height  $l_0$  of bagasse stockpile that spontaneous ignition does not occur decreases and approaches the asymptotic half-height  $l_{0,\infty}$  as the stockpile radius or length approaches infinity. A bagasse stockpile with any radius or length stored with height below the asymptotic height  $h_{0,\infty}$  (i.e.  $h_{0,\infty} = 2l_{0,\infty}$ ) is considered to be safe from spontaneous ignition for that given surrounding temperature. Using the calculated activation energy of 89 kJ/mol, the asymptotic heights for bagasse stockpiles were 10.0 m, 7.8 m, and 6.0 m for surrounding temperatures of 40°C, 45°C and 50°C, respectively.

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