Critical Ignition Temperatures
of Wood Sawdusts

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ABSTRACT

Critical ignition temperatures were estimated for fifteen species of wood
sawdust slabs, being stacked in air at normal pressure, with an adiabatic self-
ignition testing apparatus following a procedure. Assuming each stack to be in
the form of an infinite slab of a thickness of 60.96 cm (2 feet), the temperature
is estimated to range from 118 for Zelkova to 142 °C for Sitka spruce. These
values are in reasonable agreement with a few real data observed on wood sawdust
stacks of similar sizes. Zelkova and Western red cedar are relatively easy to
ignite, meanwhile Sitka spruce and Western hemlock are relatively hard to ignite.
Douglas fir and Port Orford cedar are medium in ignitability.

KEY WORDS: Critical ignition temperature; wood sawdust; self-ignition; adiabatic
oxidation reaction; thermal diffusivity; relative ignitability.

INTRODUCTION

Many research reports have appeared on various aspects of pyrolysis and
combustion phenomena of wood or woody materials. Instances, however, have been
only a few so far where the critical ignition temperatures of bulky stacks of wood
sawdusts were actually measured. As for that point, the works by Gross et al.[1],
by Akita[2], and lately by Anthony et al.[3], by John[4] and by Schliemann[5] are
quite precious.

In the present work, critical ignition temperatures of fifteen species of
wood sawdust slabs, assuming each to be stacked in hot air surroundings at normal
pressure, were estimated with an adiabatic self-ignition testing apparatus
following a procedure.

A detailed description of the apparatus was given elsewhere[6]. So the
procedure to estimate the critical ignition temperature of any stack of self-
heating substance and results when the procedure was applied to wood sawdust slabs
are mainly described in this report.

Wood species tested are as follows: Telaling (a Southeast Asian lumber),
Meranti (ditto), Sawara cedar, Japanese cedar, Japanese red pine, Japanese
cypress, Zelkova, Paulownia, Western red cedar, Douglas fir, Port Orford cedar,
Alaska yellow cedar, Western hemlock, Sitka spruce and Eli ayanskya (a Siberian
lumber).

AN EQUATION HOLDING FOR THE SELF-HEATING PROCESS UNDER AN ADIABATIC ZEROTH ORDER

ASSUMPTION

    When a sample heats spontaneously at a temperature T, eqn. (1) holds generally under an adiabatic zeroth order assumption, based on the principle of energy conservation.

$$c\rho\frac{dT}{dt} = \Delta H \cdot A \exp[-\frac{E}{RT}] \tag{1}$$

    If we assume that the temperature rise rate, dT/dt, remains effectively constant within small temperature ranges near T, we can easily integrate eqn. (1) and get the following equation after taking natural logarithms on both sides of an equation obtained by the definite integral of eqn. (1).

$$\ln \Delta t = \frac{E}{RT} + \ln[\frac{\Delta T \cdot c\rho}{\Delta H \cdot A}] \tag{2}$$

where Δt is the time required for the sample temperature to rise from T to (T + ΔT). Equation (2) can be applied to the adiabatic self-heating curve recorded precisely, by an adiabatic self-heating process recorder such as the apparatus used here, in temperature ranges of a few degrees above T. Then the gradient, a, and intercept, b, of an empirical formula, $\ln \Delta t = (a/T) + b$, can be expressed as,

$$a = \frac{E}{R} \tag{3}$$

$$b = \ln[\frac{\Delta T \cdot c\rho}{\Delta H \cdot A}] \tag{4}$$

respectively.

A RELATION DERIVED FROM FRANK-KAMENETSKII'S CRITICAL CONDITION FOR THERMAL IGNITION AND EQUATION (2)

    Frank-Kamenetskii's critical parameter δ_c for thermal ignition is expressed as,

$$\delta_c = \frac{\Delta H \cdot E r^2 A}{\lambda RT_c^2} \exp[-\frac{E}{RT}] \tag{5}$$

    Frank-Kamenetskii's critical condition for thermal ignition holds on a balance between the heating process, again based on a zeroth order reaction, and the heat loss process under non-adiabatic conditions. Incidentally eqn. (2) is concerned with the heating process alone, since it stands on the adiabatic conditions. So far as the heating process is concerned, however, both equations deal with the identical slow heating process in the subcritical state prior to ignition. Therefore it can be thought that factors such as E, A and ΔH appearing in eqn. (2) and corresponding those in eqn. (5) represent the same physical quantities, respectively.

    Taking natural logarithms on both sides of eqn. (5) and rearranging them gives,

$$\ln T_c + \frac{(E/R)}{2T_c} = \ln r + \frac{1}{2}\ln[\frac{(\Delta H \cdot A)(E/R)}{\delta_c \cdot \lambda}] \tag{6}$$

substituting eqns. (3) and (4) in eqn. (6) for (E/R) and ln($\Delta H \cdot A$) gives,

$$\ln T_c + \frac{a}{2T_c} = \ln r + \frac{1}{2}[\ln(\frac{a \cdot \Delta T \cdot c\rho}{\delta_c \cdot \lambda}) - b] \tag{7}$$

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since thermal conductivity is expressed in terms of thermal diffusivity and heat capacity per unit volume, as in eqn. (8),

$$\lambda = \alpha \cdot c\rho \qquad (8)$$

eventually we obtain,

$$\ln T_c + \frac{a}{2T_c} = \ln r + \frac{1}{2}[\ln(\frac{a \cdot \Delta T}{\delta_c \cdot \alpha}) - b] \qquad (9)$$

We see from eqn. (9) that we may dispense with direct knowledge of the individual values of ΔH, E, A, λ and c of the substance, so far as the estimation of T_c is in question. The only data required to estimate T_c value is the thermal diffusivity associated with the material, besides data, obtained with the apparatus, such as a, b and ΔT. values of r and δ_c can be assigned as desired. Methods of determining thermal diffusivity for materials are well established[7]. As a matter of course the packing density ρ of the substance in the sample cell of the self-ignition testing apparatus and of the thermal diffusivity measuring apparatus should be as equal as possible to that in the practical conditions.

STARTING PROCEDURE

A block diagram of the apparatus used here is shown in Fig. 1. Measuring procedure for oxidatively heating substances has been described elsewhere[6], but a part of it was modified in this work because of the nature of wood sawdust.

300 mg of wood sawdust sample is packed in the cell that has a hole at the bottom. Next the thermocouple for measuring sample temperature is inserted into
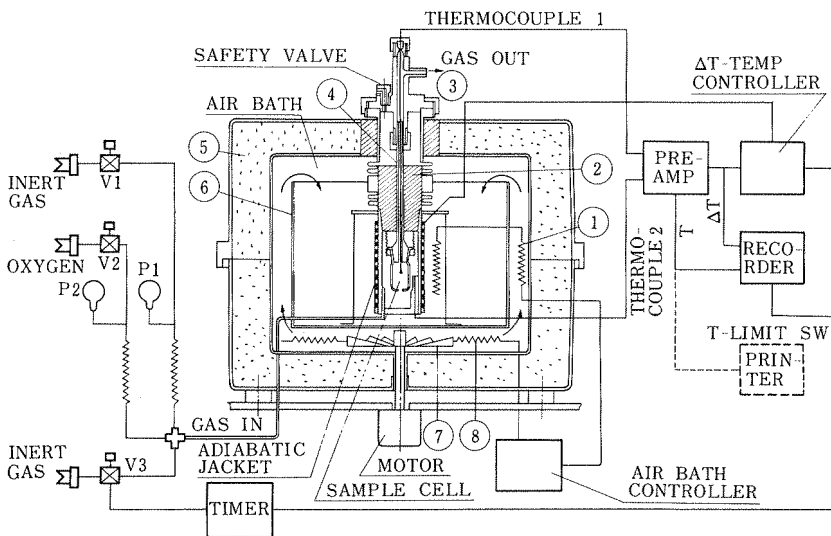

FIGURE 1. Block diagram of the adiabatic self-ignition testing apparatus. 1, Thermometer; 2, glass wool; 3, sample cell assembly; 4, silica tube; 5, glass wool; 6, wind guide plate; 7, fan; 8, heater.

the sample. Then the sample cell assembly is set in the adiabatic jacket, and nitrogen gas is supplied at a rate of 2[ml/min]. The initial starting temperature is selected as desired by setting a temperature dial on the air bath. Then the power is switched on, that is, bath heating is started. After that the apparatus is left for 270 minutes at the starting temperature in nitrogen atmosphere, to remove all of the moisture from wood sawdust and to establish thermal equilibrium. While moisture-removal process lasts, the measurement can not be started, since the endothermic effect due to vaporization of moisture masks the exothermic phenomenon due to oxidation reaction of the substrate. Then, zero-suppression procedure is carried out, and immediately after that, the supply of air at a rate of 2[ml/min], adiabatic control and recording of the heating process are commenced.

ESTIMATION PROCEDURE OF CRITICAL IGNITION TEMPERATURE OF WOOD SAWDUST

Wood strips are first prepared by cutting some 2.5 mm thick slabs from visually uniform pieces of wood block of each species using a band saw. The strips are next cut into some 2.5 mm by 2.5 mm by 2.5 mm chips with a nipper. Chips are then pulverized using an ultra centrifugal mill and size-graded to 35 to 60 mesh by sieving.

Adiabatic oxidation heating curves of each species of wood sawdust are recorded at starting temperatures ranging from 150 to 178 °C, following the starting procedure stated above. The curves for Port Orford cedar sawdust are shown in Fig. 2 as an example. In these cases it is seen that the rate of adiabatic oxidation reaction is gradually accelerated, as nitrogen atmosphere
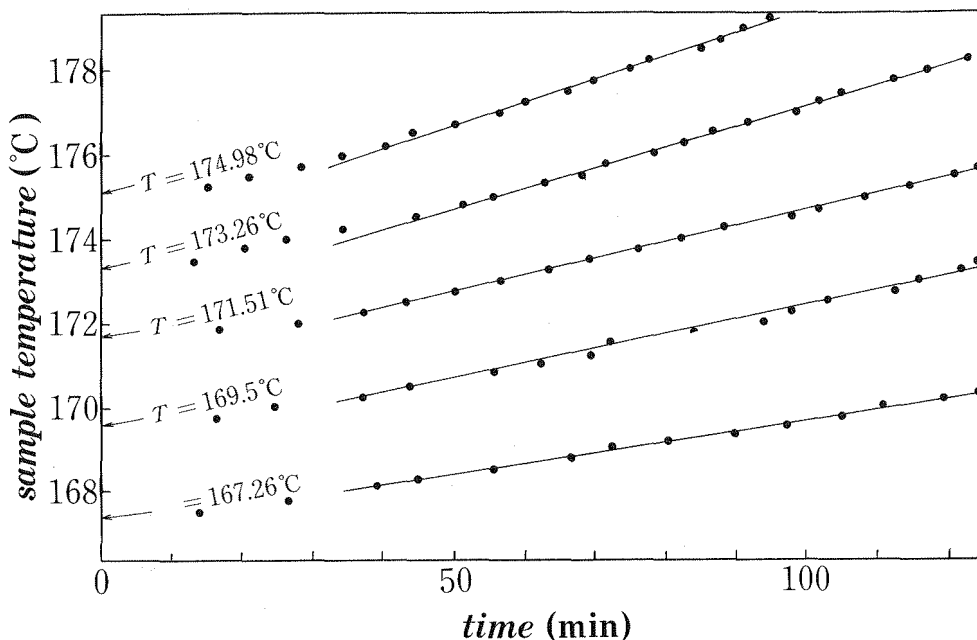

FIGURE 2. Adiabatic oxidation heating curves of Port Orford cedar sawdust.
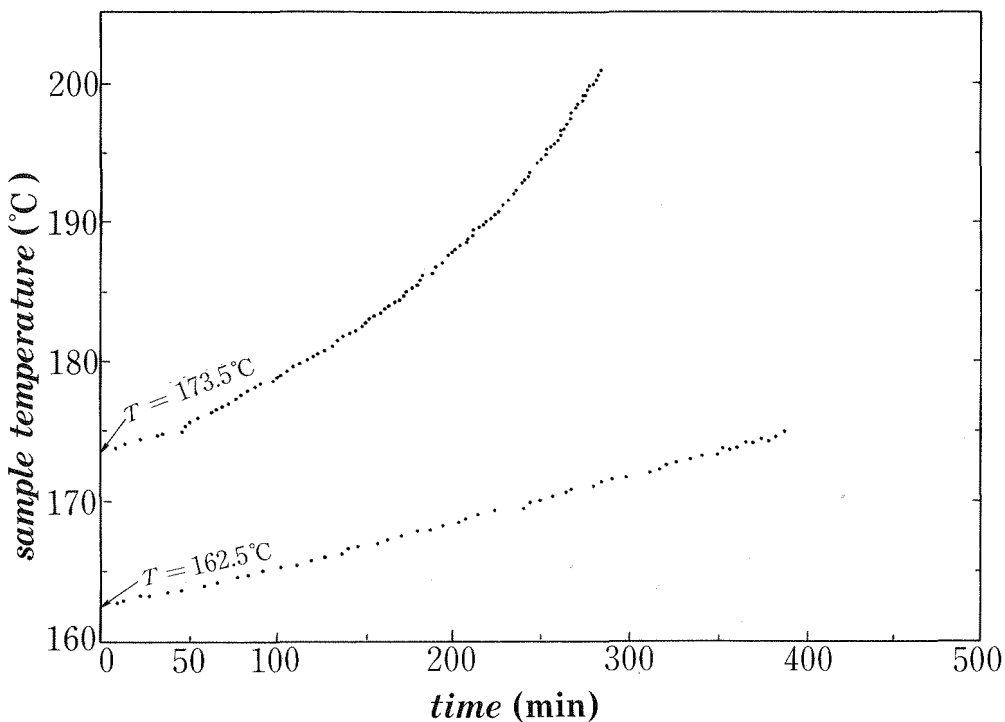
FIGURE 3. Adiabatic oxidation heating curves of Western red cedar sawdust
with wider temperature increments.

around and in the sample cell is replaced by air for about 30 minutes after the
start.

Adiabatic oxidation heating curves of wood sawdusts recorded with this
apparatus appear in most cases approximately linear. For instance, a curve is
almost linear at temperature levels of 160 to 175 °C in the case of Western red
cedar sawdust, though the temperature rise rate begins to accelerate gradually at
levels in excess of 180 °C, as shown in Fig. 3. The same thing has been reported
also by Akita[2], by Anthony et al.[3] and by Schliemann[5]. Therefore a decision
was made in this work that the gradient, $\Delta T/\Delta t$, of the linearly rising part of a
curve was used as a physical quantity corresponding to the rate of the oxidatively
heating reaction of wood sawdust.

The time, Δt min, required for the sample temperature to rise by a ΔT value
of 1.25 K is determined on each heating curve. Then ln Δt vs. 1/T plot is made
for each species. The entire plots for fifteen species of wood sawdust are given
in Fig. 4. We can see roughly from Fig. 4 the relative liability of these wood
sawdusts to heat oxidatively, or to ignite ultimately.

Values of coefficients, a and b, of eqn. (2) are determined from these plots
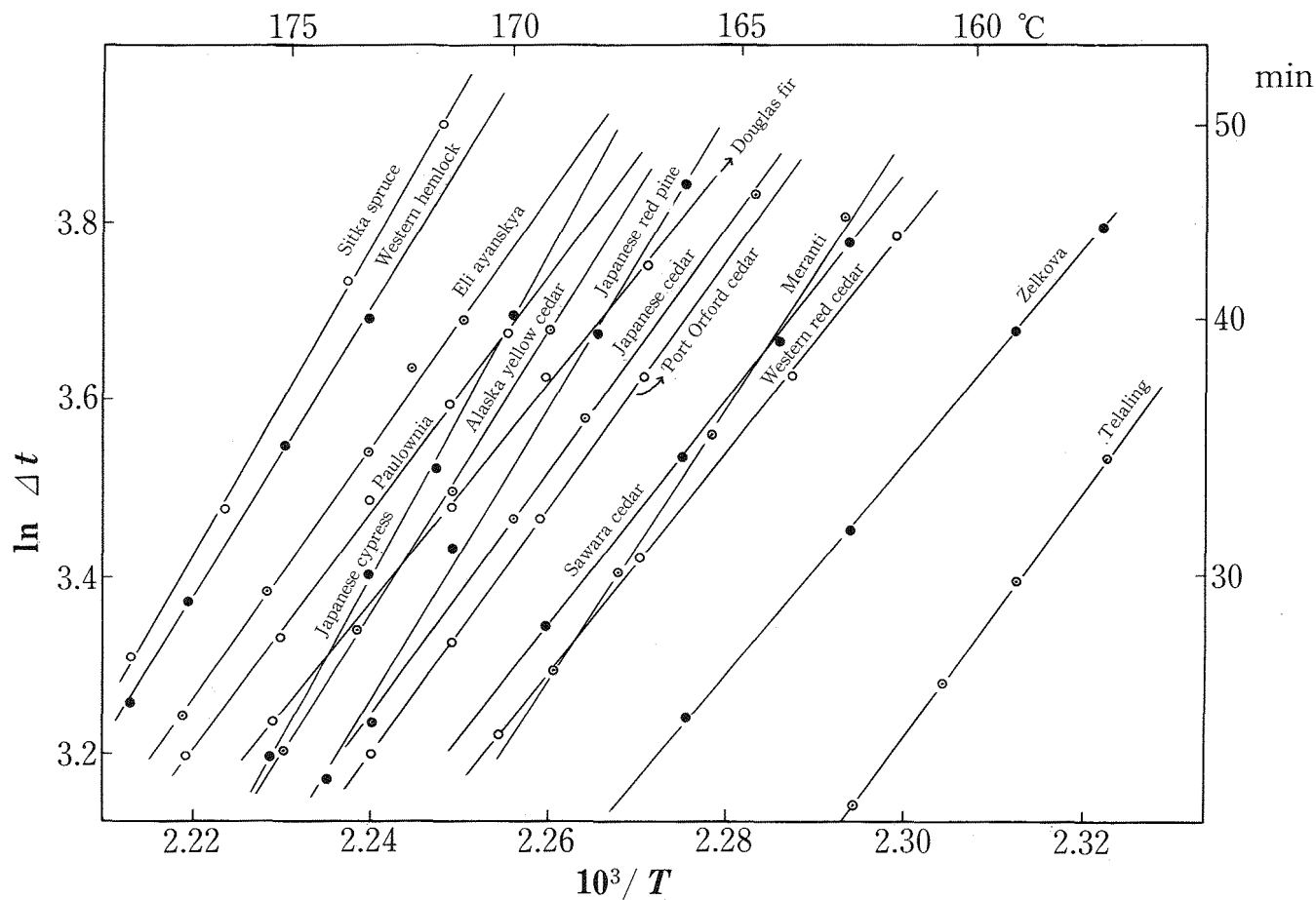by the least-squares method with a computer and are listed in TABLE 1.

FIGURE 4. The entire ln Δt vs. 1/T plots for fifteen species of wood sawdust.

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TABLE 1 Adiabatic experimental parameters of slow oxidation reaction and critical ignition
temperatures of 15 species of wood sawdust, when each stacked in a slab, 60.96 cm thick.

Wood species	a	b	α	E	ρ	T_c
					g/cm^3	$^{\circ}C$
Zelkova	11,899	−23.838	0.14	99	0.279	118
Telaling	13,736	−28.379	0.15	114	0.214	119
Western red cedar	12,487	−24.936	0.16	104	0.153	124
Sawara cedar	12,536	−24.994	0.16	104	0.173	125
Douglas fir	12,430	−24.474	0.14	103	0.197	127
Meranti	15,998	−32.881	0.15	133	0.185	130
Port Orford cedar	13,906	−27.950	0.17	116	0.138	131
Japanese cedar	13,944	−27.994	0.18	116	0.145	132
Paulownia	13,110	−25.887	0.17	109	0.173	133
Japanese red pine	16,483	−33.656	0.13	137	0.253	133
Eli ayanskya	14,478	−28.882	0.16	120	0.138	135
Alaska yellow cedar	16,124	−32.765	0.17	134	0.138	136
Japanese cypress	17,644	−36.123	0.16	147	0.131	138
Western hemlock	16,505	−33.267	0.17	137	0.131	141
Sitka spruce	17,092	−34.517	0.17	142	0.131	142

Reference data

Mixed hardwood sawdust[3], when stacked in a 61 cm cube, but in cool surroundings, 0.178   135 (obs)

Kiefernholz (German pine) sawdust[4, 5], when stacked in a sphere, 1 m diameter,   0.125   130 (obs)

The α value of wood sawdust was measured at room temperature and at 100 °C with the stepwise heating method developed by Araki et al.[7]. Values at both temperatures were much the same for each species, so the value is given in TABLE 1 as an arithmetical mean, respectively.

The form of the stack was assumed to be an infinite slab, which has a δ_c value of 0.88, of a thickness of 60.96 cm (2 feet), which is equal to 2r.

Substituting these data in eqn. (9), T_c values are obtained and are presented in TABLE 1. Wood species are arranged in order, wood sawdust of high critical ignition temperature being listed near the bottom.

RESULTS AND DISCUSSION

A possibility of heat loss due to air flow in the sample cell could not be ignored, though it would be almost perfectly covered by the adiabatic control. If that effect were serious, the true T_c value might be several degrees lower than the one determined by the procedure. Furthermore there might be some uncertainty in ln Δt vs. 1/T plots, though it would be considerably compensated by the least-squares method. As for that problem, to increase the number of the point on each plot from 4 or 5 to 10, e.g., may be helpful to increase the certainty of the plot. It is also not very pleasant that we can not make the packing density constant for each species because of the nature of wood sawdust.

For all those problems, T_c values of wood sawdust slabs estimated by calculation, following the procedure introduced above, agreed in the result reasonably with a few real data observed on stacks of similar sizes, though the species are different from those used in this work[3, 4, 5]. It thus appears that those problems anticipated above are practically negligible with wood sawdusts, at least. Then we can say that the procedure is applicable to estimate relatively and quantitatively the ignitability of any stacks of wood sawdusts.

Assuming wood sawdust to be stacked in a form of infinite slab at a thickness of 60.96 cm (2 feet), the T_c value is estimated to range from 118 for Zelkova to 142 °C for Sitka spruce. If the slab is 20.32 cm (8 inch) thick, the value is estimated to range between 147 for Telaling to 167 °C for Sitka spruce. Zelkova and Western red cedar are relatively easy to ignite, meanwhile Sitka spruce and Western hemlock are relatively hard to ignite. Paulownia may also belong under a category that is hard to ignite. Douglas fir and Port Orford cedar are medium in ignitability.

The oxidatively heating process of wood sawdusts proceeds showing an almost linear temperature rise rate in temperature ranges up to about 180 °C under adiabatic conditions.

The relative liability of wood species to heat oxidatively is scarcely recognized by thermal analysis such as TG-DTA, meanwhile it can be clearly distinguished from one species to another under adiabatic conditions.

Wood is a natural product and its composition is not homogeneous, so T_c values listed in TABLE 1 are by no means of absolute character. Nevertheless the author thinks that, although there may exist still some uncertain factors such as those stated at the beginning of this chapter, a procedure to estimate T_c values of wood sawdust stacks has been fundamentally established. The ignitability of any self-heating substances can be relatively and quantitatively determined by applying the critical ignition temperature as the criterion. So it would be interesting to see if the procedure is applicable also to other self-heating

substances.

SYMBOLS USED

A   frequency factor $[\text{mol/cm}^3 \text{ min}]$

a   coefficient expressed by eqn. (3)

b   coefficient expressed by eqn. (4)

c   molar heat capacity [J/mol K]

ρ molar density $[\text{mol/cm}^3]$

$c\rho$ heat capacity per unit volume $[\text{J/cm}^3 \text{ K}]$

E   apparent activation energy [J/mol]

ΔH molar heat of reaction [J/mol]

R   universal gas constant [J/mol K]

r   size factor [cm]

T   initial starting temperature [K]

T_c critical ignition temperature [K]

t   time [min]

δ_c Frank-Kamenetskii's critical parameter for thermal ignition

α thermal diffusivity $[\text{cm}^2/\text{min}]$

λ thermal conductivity [J/cm min K]

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