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Characteristics of Downward Deep-seated Fire in Radiata Pine Based on Changes in Volumetric Mass Density

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The demand for and the consequent production of porous materials, such as wood, increase with industrial development and income. If a smoldering fire occurs in a porous material such as wood flour, it is difficult to find the fire location because of the development of a downward deep-seated fire. In this study, a down-scaled downward deep-seated fire model was adopted for wood flour to experimentally and theoretically elucidate the propagation phenomena of the downward velocity of deep-seated fires and subsequently predict their location. The experiment was performed on radiata pine wood flour with the density range of 0.2038 to 0.2343 g/cm^3. Different tendencies were observed quantitatively in the downward temperature profiles with the changes in the volumetric mass density of the wood flour. Based on these results, it can be concluded that the deep-seated fire propagation speed is in the range of 0.0014 to 0.0018 cm/s. The practical applications of this result would be in effective extinguishing of fires in wood flour factories and silos by predicting the fire site based on the determination of the speed of propagation of the downward deep-seated fire.

INTRODUCTION

Wood has been used by humans in many ways for thousands of years. The production of sawn wood, wooden panels, paper, paperboard, and industrial timber tends to increase when the human population, economic growth, and the use of biomass increase (Food and Agriculture Organization 2014). In particular, the production and consumption of wooden panels such as plywood, veneer, particle board, and fiber board are all expected to increase at an average rate of 3% from 2016 to 2030 (Food and Agriculture Organization 2014). Wooden panels are made from wood shavings and their large area allows for easy contact with oxidizers. Therefore, smoldering combustion can occur readily in these panels (Korea Forest Research Institute 2012).

As per general practice, wood is heated slowly up to 200–230 °C in a humid and inert gas environment (Esteves and Pereira 2008). Wood is a complex composite material, consisting of cellulose (*ca*. 40 to 45%), hemicelluloses (*ca*. 20 to 25%), lignin (*ca*. 20 to 30%), and low-molecular-mass compounds as volatile and non-volatile extractives (3 to 5%) (Wikberg and Maunu 2004). These conditions may give rise to deep-seated fires. Carbon and hydrogen burn well naturally, and the oxygen generated during the thermal decomposition of cellulose further aids the combustion of carbon and hydrogen, even when

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the concentration of the atmospheric oxygen is 16% or lower (Ohlemiller 1985). Smoldering combustion is the initial stage of deep-seated fires and is defined as a fire burning far below the surface such that it propagates by penetrating porous materials, which act as fuel, and causes a reaction on their surfaces. In the case of a deep-seated fire, if there is an insufficient amount of oxygen present within the reaction zone during the combustion process, the flame cannot grow normally as it does in a generic fire. Thus, the chemical reaction progresses without a flame. As a smoldering combustion reaction occurs largely in porous materials containing air pores, the combustion process propagates without convective heat transfer or a continuous supply of the oxidizer. If a general reaction begins, it is difficult to discover or extinguish the fire, because an exothermic reaction occurs within the fuel (Hall 2004). Therefore, a smoldering combustion reaction is likely to occur in areas where the oxidizer is insufficiently supplied or if the environment has a small amount of the oxidizer flowing in from the outside (Dosanjh *et al.* 1987). As evidenced by the recent smoldering fires in wood flour factories and silos, the wood flour flame results in smoldering combustion, which is very dangerous. There was a recent case of a deep-seated fire, namely, a woodchip fire, at a recycling site in South Wales. The fire occurred in Heol Llan, Coity, Bridgend at 03:30 BST on September 19, 2016. The store where the fire occurred contained nearly 3000 tons of wood chips, and the fire lasted for eight days until it was completely extinguished on September 26.

Further, while there have been many studies on deep-seated fire, there has been little research on wood flour fires. This study aimed to evaluate the effects of the volumetric density of wood flour on the possibility of smoldering fires occurring in wood flour factories and silos. Experiments performed on wood flour in this study resulted in a downward deep-seated fire in the state of natural convection, and the changes in the density of the wood flour were evaluated. The temperature within the deep-seated fire was measured as a function of time by installing multiple thermocouples along the depth direction from the reactive surface. The velocity of the smoldering combustion, and its characteristics of propagation were identified based on the measured results. In addition, the temperature of the reactive surface was predicted by using a numerical model that took into consideration the amount of oxidizer flowing inward onto the reactive surface and the porosity of the fuel, while assuming that the first step in the reaction did not involve thermal decomposition. The results obtained using the numerical model were compared with the experimental results.

Smoldering Combustion

Smoldering combustion refers to the flameless combustion that occurs largely in porous combustibles. It is also considered the initial stage of fire because no flames are generated. Smoldering combustion can be classified based on the propagation direction, inflow direction of the oxidizer, and buoyancy force. The one-dimensional propagation of smoldering can be classified as forward and downward. Forward combustion means that the combustion reaction progresses in the same direction as the thermal buoyancy, while backward combustion means that the combustion reaction progresses in the opposite direction of the thermal buoyancy.

According to Bowes, the oxidation of carbides plays a key role in most of the spontaneous combustion propagation processes. Furthermore, in the case of all materials that form carbides in substantial amounts during thermal decomposition, the possibility of smoldering combustion exists (Bowes 1984). Palmer investigated the propagation of smoldering using layers of several types of sawdust with different thicknesses and reported

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that smoldering propagated upwards, while Dosanjh revealed that to reach a normal state, the smoldering reaction must emit enough energy to heat the inward flowing air (Palmer 1957; Dosanjh *et al.* 1987). In addition, Frandsen studied downward smoldering propagation by using the horizontal peat deposits found on the forest surface as a model fuel (Frandsen 1991). Ohlemiller evaluated the arrangement method and the dependence of the smoldering velocity on a cellulose insulation layer with a thickness of 0.10 m to 0.11 m (Ohlemiller 1990). Chirag *et al.* (2011) experimentally assessed the vertical smoldering combustion velocity of teak wood and cow dung particles.

Several researchers have performed experimental and analytical studies by focusing on the impact of the oxidizer to evaluate the effects of the inflow velocity, inflow composition, and type of porous material being burned. Furthermore, the levels of the toxic gases generated during combustion, the fire transfer mechanism, and the various fire extinguishing methods available have also been studied (Drysale 1987; Fatehi and Kaviany 1994; Torreo and Fernandez-Pello 1996; Kim and Rie 2016). Recently, the economic losses caused by deep-seated fires have also been studied using a wetting agent (Kim and Rie 2017). However, there have been few studies on radiata pine or on the effect of wood flour on reducing the fire damage caused by radiata pine. Thus, it is necessary to evaluate the possibility of smoldering combustion in the wood flour of radiata pine.

EXPERIMENTAL

Materials

The wood flour of radiata pine (*Pinus radiata*) (Southland, New Zealand) was selected as the experimental material in this study because of its high demand around the world. *P. radiata* is a versatile, fast-growing, medium-density softwood and is suitable for a wide range of uses (Mead 2013). The grain size of the wood flour used, which was separated by sieving, was 0.1 mm to 0.5 mm. No additives were used during the production of the wood flour, and the entire wood flour sample was produced using the same processes to ensure material homogeneity. Table 1 shows the composition of the wood flour used in this study. The composition was determined though X-ray fluorescence (S4 PIONEER, BRUKER, German) measurements according to ISO 12677 (2011). The analysis concentration range is from sub ppm to 100%. As shown, over 99% of the wood flour was composed of carbon and hydrogen, while oxygen, nitrogen, mineral ash, and other components made up the remainder of the composition.

Table 1. Composition of Wood Flour as Determined by XRF Analysis

Compound	Concentration (%)	Compound	Concentration (%)
CH_2	99.5	MgO	0.0603
CaO	0.172	Na_2O	0.0409
K_2O	0.0837	SO_3	0.0321

Measurement of temperature of reactive surface during smoldering

Figure 1 shows a schematic diagram of the apparatus used to measure the temperature profile as smoldering progressed downward. An experimental ignition method based on the ISO 5660-1 standard was used to ignite the top surface of the wood

flour. The heat flux from the cone heater was set to be constant at 50 kW/m^2 until ignition. The heater was situated 25 mm upwards from the sample container and was removed once the sample was ignited. The sample container was made of stainless steel and had a diameter of 100 mm and height of 200 mm. The top and bottom sides of the container were covered with a mesh with dimensions of 0.3 mm (wire diameter) × 1 mm (gap). Five thermocouples (type K, 1.6 mm in diameter, Misumi Korea Corporation, Seoul, Republic of Korea) were installed laterally in the container at intervals of 20 mm, to measure the temperature at the center of the container during the downward smoldering propagation. The temperature measurements were begun as soon as the top surface was ignited, with the temperature being measured every second.
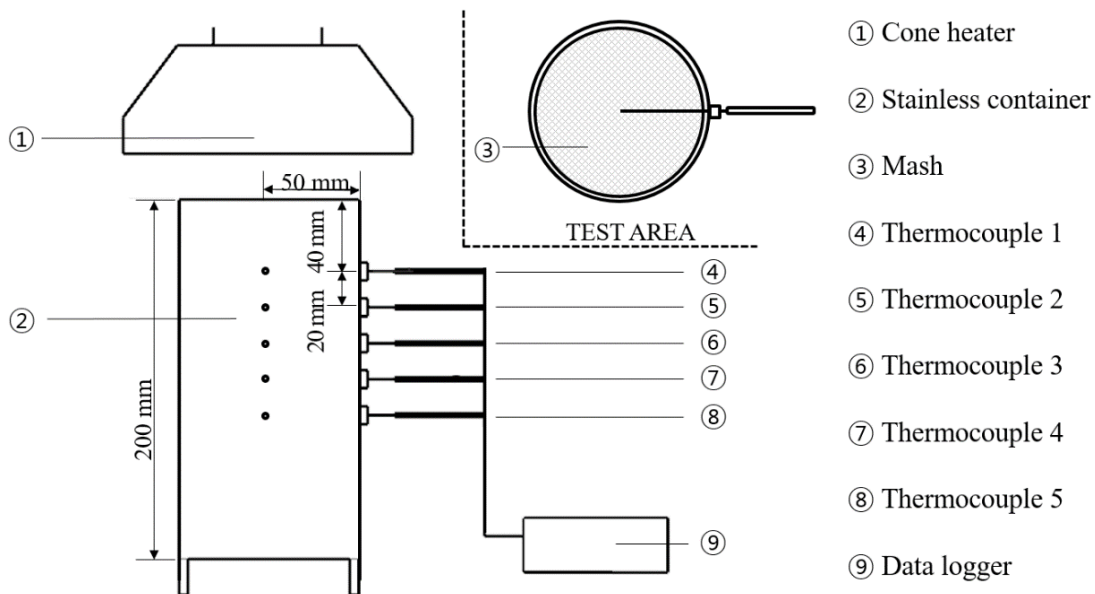

Fig. 1. Schematic diagram of experimental apparatus

Table 2 shows the densities of the wood flour samples used in this study. The density for Case 1, 0.2038 g/cm^3, was the density measured when the wood flour was placed in the experimental container under gravity conditions, that is, with no external force/pressure being applied. The densities corresponding to the other experimental conditions were 0.2089 (Case 2), 0.2140 (Case 3), 0.2242 (Case 4), and 0.2343 (Case 5) g/cm^3.

Table 2. Densities of Experimental Samples

	Mass (g)	Increase (%)	Density (g/cm^3)
Case 1	320.0	0 (Standard)	0.2038
Case 2	328.0	+ 2.5	0.2089
Case 3	336.0	+ 5	0.2140
Case 4	352.0	+ 10	0.2242
Case 5	368.0	+ 15	0.2343

Numerical Analysis

Model for predicting temperature distribution during smoldering reaction

The downward smoldering combustion was also evaluated numerically. Figure 2 shows a model of downward smoldering propagation based on natural convection. In the model, the smoldering reaction propagates downward.
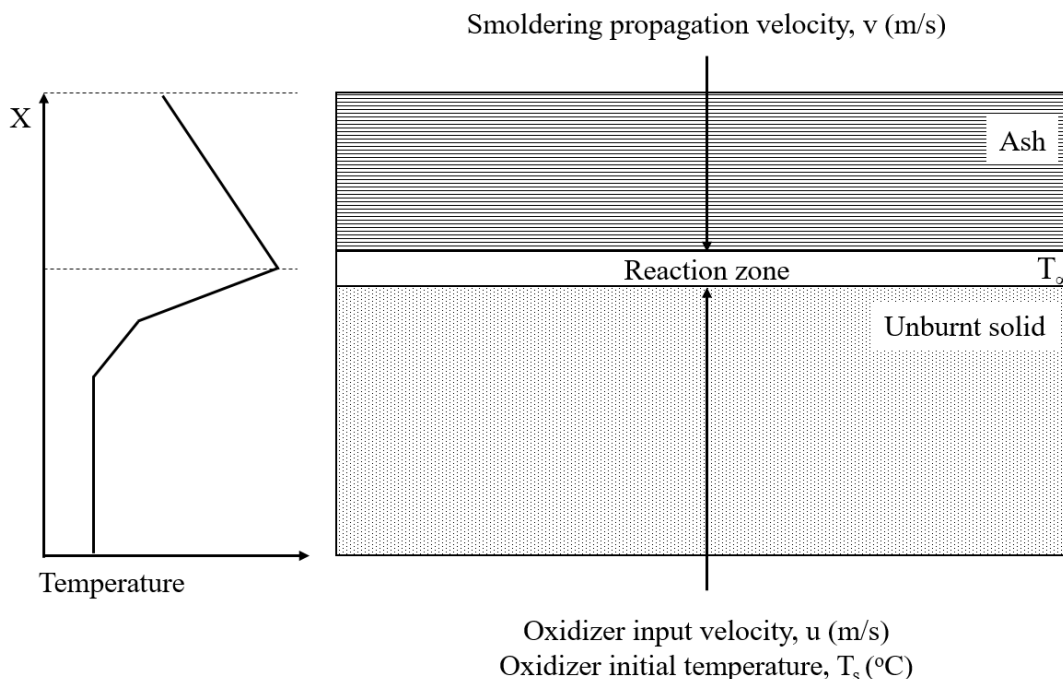

Fig. 2. Simplified smoldering propagation model and combustion velocity

There was an inflow of the oxidizer onto the reactive surface from the side of the unburned fuel simultaneously with the smoldering process. According to Ohlemiller (1991), the smoldering process can be divided into two stages: the thermal decomposition process and the oxidation process. The thermal decomposition process was omitted from the overall reaction process owing to the amount of energy consumed during pyrolysis being minimal as compared to that released from the reaction surface. Therefore, the overall temperature distribution was not affected. In particular, Dosanjh and Pagni (1987) obtained an analytical solution for the temperature distribution and propagation velocity during the smoldering process by using the activation energy asymptotic method. Schult *et al.* (1995) extended this work and determined the reaction velocity and temperature distribution by introducing several dimensionless numbers.

In this study, the temperature distribution on the reactive surface was calculated under the condition that the temperature of the reactive surface was known. According to Turns (2000), the temperature distribution on the reactive surface is determined by the oxidizer that is present in the wood flour and the pores of the oxidizer if one assumes that there is no thermal decomposition. The reaction for smoldering combustion in the absence of the thermal decomposition process can be simplified as described in Eq. 1.

Unburnt solid (s) + Oxidizer (g) $\rightarrow$ Ash (s) + Combustion gas (g) + Energy released (1)
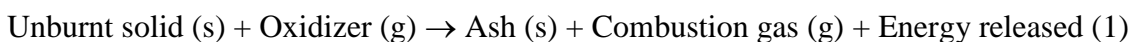
Furthermore, the mass flux of the solid flowing inward onto the reactive surface as well as the gas mixture of oxygen and the combustion gas is given by Eq. 2,

$$\dot{m}_s^{"} = (1 - \emptyset)\rho_s v$$
$$\dot{m}_g^{"} = \rho_g(u + v) \tag{2}$$

where v is the inflow velocity of the solid (m/s), u is the inflow velocity of oxygen (m/s), $\emptyset$ is the porosity of the solid, ρ_s is the density of the solid (kg/m^3), ρ_g is the density of oxygen (kg/m^3), $\dot{m}_s^{"}$ is the mass flux of the solid (kg/m^2 s), $\dot{m}_g^{"}$ is the mass flux of the gas mixture (oxygen and combustion gas (kg/m^2 s)).

Based on the law of conservation of mass, the mass flux can represented by Eq. 3.

$$\dot{m}^{"} = \dot{m}_s^{"} + \dot{m}_g^{"}$$
$$= (1 - \emptyset)\rho_s v + \emptyset\rho_s(u + v)$$
$$= \text{const.} \tag{3}$$

In general, the pores in wood flour appear oval when viewed under a microscope. However, in this study, it was assumed that the pores containing the oxidizer were spherical and that the heat transfer of a single round oxidizer of those present on the reactive surface which is processing downward represented the entire temperature distribution. If the oxidizer entity is spherical and the material properties remain constant under the assumption that the Lewis number is one, the one-dimensional energy equation can be represented as shown in Eq. 4,

$$\frac{d\left(r^2\frac{dt}{dr}\right)}{dr} = \frac{\dot{m}c_o}{4\pi k_o}\frac{dT}{dr} \tag{4}$$

where k_o (W/m K) is the coefficient of thermal conductivity of the oxidizer. The boundary conditions are $T = T_s$ (temperature of the reactive surface (K)) and $T = T_\infty$ (inflow temperature of the oxidizer (K)) at $r = r_s$.

If one assumes that $c_o/4\pi k_o = Z$ for convenience and applies the integral and boundary conditions, then Eq. 5 can be derived, and the temperature distribution on the reactive surface can be predicted through calculations.

$$T = \frac{(T_\infty - T_S)\exp\left(-\frac{Z\dot{m}}{r}\right) - T_\infty\exp\left(-\frac{Z\dot{m}}{r_S}\right) + T_S}{1 - \exp(-\frac{Z\dot{m}}{r_S})} \tag{5}$$

In this study, the temperature distribution on the reactive surface was calculated based on the material properties listed in Table 3. The temperature of the reactive surface was considered as the actual temperature measured during the experiments. On the other hand, the temperature of the inflowing oxidizer was taken to be that of the ambient (297.15 K).

In addition, the mass flux of the solid onto the reaction surface was set to 0.004 kg/m^2. However, the solid mass flux was taken to be 0.002 kg/m^2 based on the results reported by McAllister, since wood flour was used in this study (McAllister *et al.* 2010).

Table 3. Material Properties for Calculations

Initial temperature of inflowing oxidizer (K)	T_S		297.15
Temperature of reactive surface (K)	T_∞	Case 1	606.25
		Case 2	565.15
		Case 3	503.05
		Case 4	503.95
		Case 5	498.45
Mass flux of solid inflowing onto reactive surface (kg/m² s)	$\dot{m}_S$		0.002
Mass flux of gas inflowing onto reactive surface (kg/m² s)	$\dot{m}_g$		0.001
Diameter of sphere of oxidizer (m)	r_s		0.001

RESULTS AND DISCUSSION

Results of temperature measurements

There was a change in the temperature when there was a change in the density of the wood flour. Figure 3 and Table 4 show the maximum temperature as measured by thermocouples (T/C) 1–5 with changes in the volume density of the wood flour. The temperature measured by thermocouple 1 in Case 1 was 333.1 °C, which was the highest temperature recorded.

Furthermore, the temperature measured by T/C 1 in Case 2 was 292 °C, which was approximately 41 °C lower than that for Case 1. The temperatures for Case 3 differed with the location of the thermocouples. When there was an increase in the density, the temperature decreased. Thus, the average difference in the temperatures measured by the different thermocouples was 60 °C for Case 1, 56.5 °C for Case 2, 43.4 °C for Case 3, 43.8 °C for Case 4, and 42.8 °C for Case 5. During the experiments, the flameless fire did not transform into a fire with a flame. Under the conditions investigated, it was observed that the greater the increase in the volume density of the wood flour, the greater was the decrease in the temperature of the flour. However, for Cases 3, 4, and 5, where the density of the wood flour was higher than 0.214 g/cm³, the maximum temperature difference was less than 5 °C, as shown in Table 4. When the volume density of wood flour was increased, the amount of oxidizer in the wood flour and the amount of oxidizer inflowing onto the reactive surface both dropped.

It is generally known that the ignition temperature of wood flour ranges between 225 and 275 °C (Lowden and Hull 2013; NIST 1947). If there are abrupt changes in the supply of the oxidizing agents to the ignition source at depths ranging from 40 to 60 mm at temperatures above 225 °C, then there is a possibility of the process transitioning to flaming combustion. In addition, if a smoldering fire occurs on the surface of wood flour with a density of 0.2038 g/cm³, it is necessary to extinguish it to a depth of 60 mm. Reignition can be limited by extinguishing the fire with water until a depth of 40 mm in the case of wood flour with a density of 0.2089 to 0.2343 g/cm³.
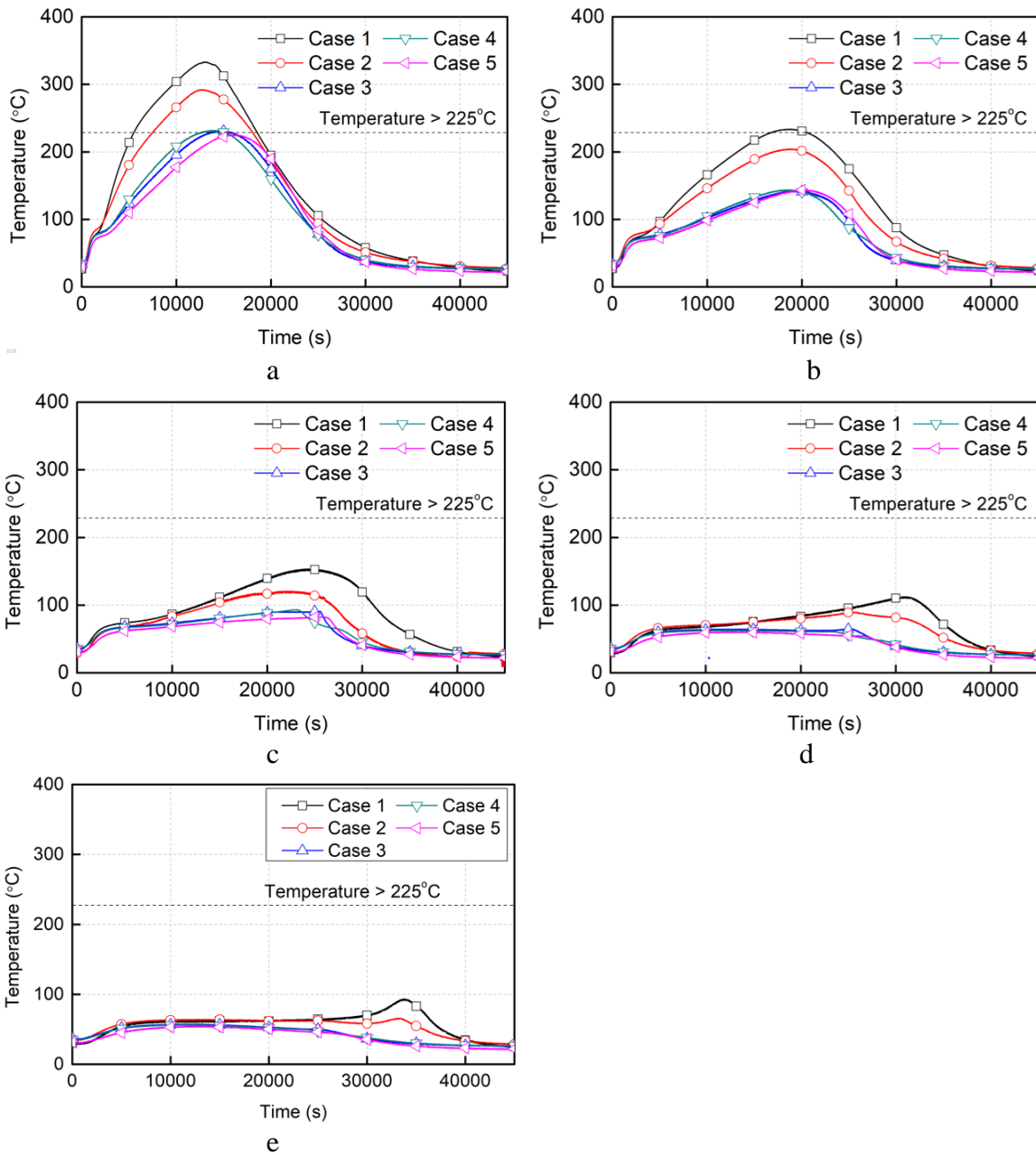
Fig. 3. Temperatures measured during smoldering as functions of time for samples with different densities. a: T/C 1, b: T/C 2, c: T/C 3, d: T/C 4, and e: T/C 5

Comparison of experimental and numerical analysis results

Figure 4 shows the temperature along the depth direction (T/C 2; T/C 3; T/C 4; T/C 5) corresponding to the time when the temperature of the reactive surface (T/C 1) had reached the maximum value. The data indicate that the temperature decreased as the distance from the reactive surface increased. Based on the results for Cases 1–5, it can be seen that the temperature of the site located 50 mm below the reactive surface did not exceed 100 °C.

Table 4. Maximum Temperatures Recorded at Different Thermocouple Locations

Case \ T/C	Temperature (°C)				
	1	2	3	4	5
1	333.1	233.6	153.4	115.5	93.1
2	292.0	204.3	120.5	89.6	65.7
3	230.9	142.2	91.2	64.9	57.3
4	231.8	143.8	93.3	62.7	56.4
5	230.3	143.5	87.7	65.3	59.1
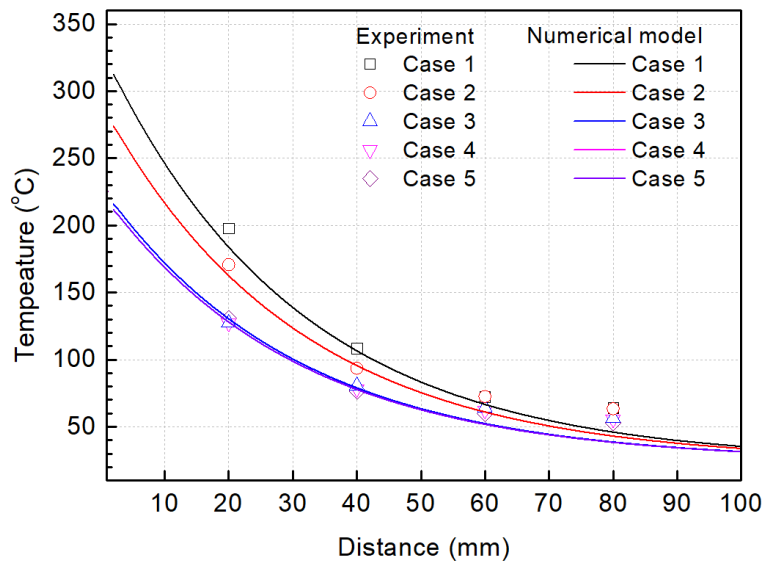
Fig. 4. Comparison of temperatures along depth direction from reactive surface

The solid line represents the results calculated using the expression for the temperature distribution on the reactive surface and the material properties as described in the previous section. The reaction velocity on the reactive surface and the heat transfer effect of the solid and gaseous products in the surface were also taken into consideration.

With regards to the calculated values, it was also observed that the temperature of the reactive surface decreased, eventually becoming equal to the room temperature. When the calculated and experimental values were compared, it was observed that the overall trends in the values were similar. However, the theoretically determined values were lower by 15 °C in two ranges, 0 mm to 20 mm and 60 mm to 80 mm. Furthermore, the error corresponding to Case 1 was larger than that for Cases 2 through 5.

This error was induced by the wood flour and oxidizer not being equally distributed in the experimental container. Thus, the insulating effects of the stainless container and the oxidation of the resulting char were not considered in the calculations. However, even though the oxidation of the char was not considered, it was assumed that, with respect to the temperature distribution on the reactive surface, heat transfer was caused primarily by the oxidizer.
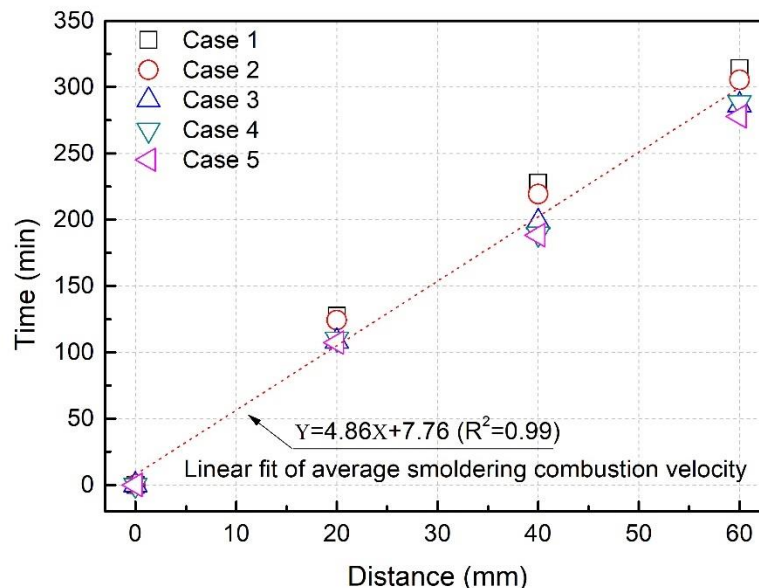
Smoldering combustion velocity of deep-seated fire

The speed at which the smoldering reaction front moved through the sample of wood flour at the vertical centerline is shown in Table 5 and Fig. 5. The smoldering combustion velocity was determined based on the estimated maximum temperature for each density and using the locations of the thermocouples (40, 60, 80, 100, and 120 mm) as an indicator for when the smoldering reaction reached a thermocouple. This allowed us to calculate the average velocity between two thermocouples.

Table 5. Smoldering Combustion Velocity of Wood Flour for Different Cases

	Density (g/cm^3)	Smoldering combustion velocity (cm/s)
Case 1	0.2038	0.00146
Case 2	0.2089	0.00141
Case 3	0.2140	0.00133
Case 4	0.2242	0.00134
Case 5	0.2343	0.00129

There were slight changes in the propagation velocity with changes in the density of the wood flour. Case 1 exhibited the highest velocity at 0.00146 cm/s. Case 2 showed a slope difference of 3% on average when compared to Case 1, with the smoldering combustion velocity corresponding to Case 2 being 0.00141 cm/s. In addition, for Case 3 the velocity was 0.00133 cm/s, for Case 4 it was 0.00134 cm/s, and for Case 5 it was 0.00129 cm/s.

Fig. 5. Smoldering combustion velocity as function of distance and linear fit

Thus, it was possible to estimate the speed at which the fire propagated from the location of the fire source in the wood flour sample with respect to time by using the equation $Y = 4.8\underline{6} X + 7.76$ (R^2=0.99).

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Figure 6 shows the smoldering combustion velocity for various materials in the state of natural convection as reported in previous studies, as well as the smoldering combustion velocity for wood (Egerton *et al.* 1963; Kinbara *et al.* 1967; Bowes 1984; Chirag 2011).
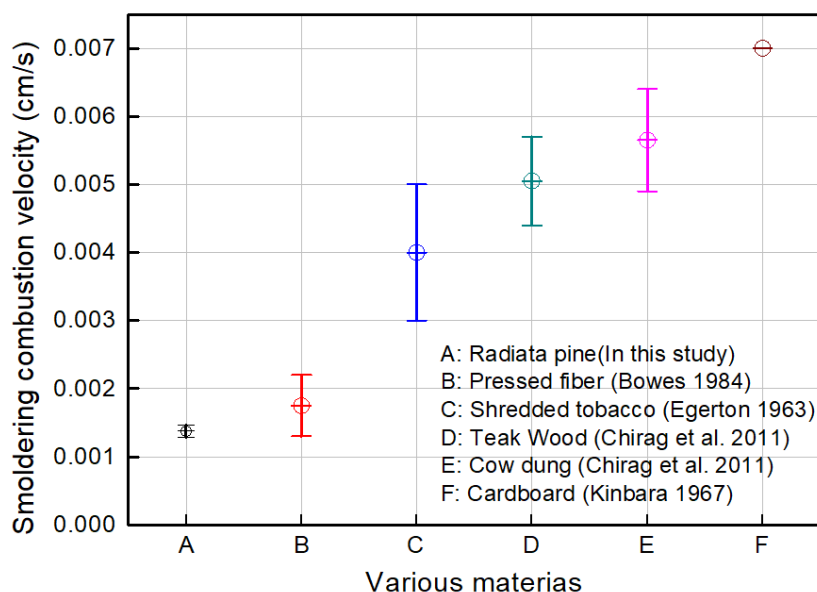

Fig. 6. Comparison of smoldering combustion velocities for different materials

In this study, the experiments were performed under natural convection in the absence of an oxidizer supply; this affected the smoldering combustion velocity. Thus, because the experiments in this study were not performed under the same conditions as those used in the previous studies, the smoldering combustion velocities could only be compared qualitatively. It was observed that, when the volume density of the wood flour ranged between 0.2038 g/cm^3 and 0.2343 g/cm^3, the smoldering combustion velocity ranged between 0.0014 cm/s and 0.0018 cm/s. These values are similar to the propagation velocity for compressed fibers and nearly 2.1 times lower than that for shredded tobacco.

As can be seen from Fig. 6, the downward transition of the temperature was slow. If one can predict the location of the smoldering fire in wood flour, it will be possible to extinguish and it more efficiently. This will help fight fires that occur in wood flour in silos and wood flour processing factories and to keep them from reigniting.

The results described were obtained through down-scale experiments performed in a laboratory environment and demonstrated that the temperature transition pattern will vary based on the type of wood flour and additives used.

However, the results of this study should be of use in the prevention of fires in silos and wood flour processing factories, as they will allow one predict the rate of transition in the temperature of wood flour and stop the propagation of smoldering fires. Moreover, they should make it possible to determine whether the wood flour has reignited sooner and predict the location of the fire source, and extinguish it if data are accumulated through research on a variety of experimental conditions based on more wood types.

CONCLUSIONS

Smoldering combustion is difficult to study because of the limited repeatability and reproducibility of the related laboratory experiments. The results of the numerical analysis of smoldering fire performed in this study were similar to those determined experimentally. The internal temperature of a smoldering fire was measured using K-type thermocouples, which was performed to analyze the propagation characteristics of the smolder temperature in response to changes in the volumetric density of the wood flour of radiata pine. The following conclusions could be drawn by modeling the smoldering combustion reaction on the reactive surface while omitting the initial thermal decomposition process.

1. A difference in the temperature was observed with changes in the volume density of the wood flour in the range of 0.2038 to 0.2343 g/cm^3. The corresponding maximum temperature at the center of the experimental container was 331.1 to 230.3 °C.

2. The difference in the temperature corresponding to volume densities of 0.2140 g/cm^3, 0.2242 g/cm^3, and 0.2343 g/cm^3 was less than 10 °C. This was true for nearly all density ranges and indicated that the temperature did not decrease when the volume density was 0.2140 g/cm^3 or higher.

3. It was found that the oxidizer had a remarkable effect on heat propagation on the reactive surface. Furthermore, in terms of the change in the volume density of the wood flour, the smoldering figure spread at a rate of 0.0014 to 0.0018 cm/s, depending on the volume density.

4. The difference in the temperature of the reactive surface of the wood flour sample was measured. Both theoretical calculations and experimental results showed that it varied with the measurement location. However, for all the density ranges, the temperature difference was within 15 °C.

5. The location of the fire source could be estimated using the thermocouples installed in the wood flour and based on the equation $Y = 4.86 X + 7.76$ (R^2=0.99).

6. In case of fires occurring on the surface of wood flour with a density of 0.2038 g/cm^3, it is necessary to extinguish the fire to a depth of 60 mm. Reignition can be prevented by extinguishing to a depth of 40 mm from the surface of the wood flour when the density is in the range 0.2089 to 0.2343 g/cm^3.

ACKNOWLEDGMENTS

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