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An Experimental Study on Autoignition of Wood

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1. Introduction

Every long dry season, serious forest fires periodically occur at several islands in Indonesia such as Kalimantan Island and Sumatra Island, result in loss of natural resources and smoke that disturb the air and marine traffic. Autoignition on solid fuel such as wood often across the forest without any source of fire. This spontaneous ignition is a complex interplay of chemistry, heat transfer, and mass transfer, which is caused by the heat radiation around the wood object. Because of the hazardous and complexity of autoignition, the process of this autoignition needs to be confirmed by experiments.

Flaming ignition refers to the appearance of a flame at the surface of a material, which has been exposed to some type of external heating. The existence of the visible flame is a clear indication of the chemical reaction between oxygen and fuel. Basically, three conditions must be satisfied to achieve flaming ignition (Kashiwagi, 1974). These are:

- (1) the mixture of fuel and oxygen must be within the flammability limits;
- (2) the temperature of the gas phase in the boundary layer should be sufficiently high to initiate the combustion reactions, and;
- (3) the extend of the local high temperature zone must be large enough to overcome heat losses during the ignition period.

The initiation of flaming ignition may be spontaneous or piloted. The latter occurs in the presence of an ignition source, such as a flame or an electrical spark. Spontaneous ignition or autoignition is another type of flaming ignition. Like piloted ignition, the autoignition could occur due to external heating but in the absence of an ignition source. Alternatively, autoignition may occur because of self-heating. This type of ignition is achieved when there is a balance between heat generation and heat dissipation. The temperature of the solid fuel goes up when heat is generated at a faster rate than the heat being dissipated. Eventually, the solid reaches a critical state at which a runaway reaction takes place leading to spontaneous ignition (Tsuchiya and Sumi, 1977; Hill and Quintiere, 2000). The critical conditions might be achieved when either the temperature of the fuel reaches a critical ignition temperature (Yang, 1961) or when the temperature of gaseous fuel-air mixture in the boundary layer around the fuel raises to the so-called auto-ignition temperature (Hill and Quintiere, 2000). The self-heating type spontaneous ignition has been extensively studied. The pioneering work Frank-Kamenetskii (1955) laid the foundation of the work in this area. According to Frank-Kamenetskii theory the volumetric rate of heat generation due to self-heating can be expressed in term of the following Arrhenius type relationship:

$$\dot{q}''' = A \Delta H_c e^{-E/RT} \quad (1)$$

where \dot{q}''' is energy generation per unit volume, A is pre-exponential factor, ΔH_c is heat of combustion, E is the activation energy, R is the gas constant, and T is temperature (Hill and Quintiere, 2000). Spontaneous ignition occurs when \dot{q}''' is equal to heat losses due to convection and radiation.

Despite its importance in industrial settings, spontaneous ignition due to self-heating is rarely the cause of fire in residential buildings mainly because materials susceptible to self-heating are not usually stored in these buildings at quantities prone to self-heating. Spontaneous ignition due to external heating, however, is sometimes the cause of forest fires. For this reason spontaneous ignition of cellulosic material by radiation (external heating) has been studied by several researchers including: Simms (1960), Simms and Law (1967) and Gandhi and Kanury, (1989). Similar to the case of piloted ignition the influence of external (e.g. heat flux) and internal parameters (e.g. structural properties, moisture content) was investigated. Past studies have established that under similar conditions the ignition delay times associated with spontaneous ignition are longer than those of their piloted ignition counterparts (e.g. Bilbao et al., 2001 and Babrauskas, 2002). The impacts of parameters, such as the moisture content, external heat flux, and structural properties on spontaneous ignition due to external heating have been found to be very similar to the case of piloted ignition. Experiment on three kinds refuse derived fuel fire inception by spontaneous ignition by using TG-DTA has been conducted by Gao (2004). The range of pyrolysis temperature was 150-550°C, and the activation energy was 89.82 kJ/mol.

Poespowati et. al (2001, 2004) conducted an experimental study on re-ignition characteristics of Australian wood-based materials in order to investigate the role of wood porosity on its re-ignition characteristics. Their experiments were carried out on a set of wood samples with various levels of porosity at heat flux level between 40 – 60 kW.m⁻² by using a modified mass-loss cone calorimeter. Results of the study were consistent with their previous experimental data on surrogate ceramic samples revealing that the effect of porosity on the re-ignition delay time was significant at all heat flux levels particularly those in excess of 50 kW.m⁻².

Later on, Poespowati (2007b) carried out an experimentally study on fire properties of eight kinds of Indonesian wood (*akasia*, *sengon*, *bangkirai*, *waru*, *kempas*, *meranti*, *gelam*, and *ulin*) exposed to the irradiance heat flux between 17-41 kW.m⁻². It was found that low density wood will burn faster than the high density wood and the higher the incident heat flux, the quicker the ignition time, inversely, the lower the ignition temperature. The results for autoignition time was between 100-200 second, and the autoignition temperature was between 350-600°C. Wood density is inversely proportional to wood porosity, which is a measure of void volume in the structure of the wood. Generally, porosity refers to the total volume of pores ranging from meso-and micro- to macro-pores. Much of these pores are the so-called closed pores, which are inaccessible. However, what is important in ignition is the percentage of open pores, which are accessible to gas (e.g. combustion products) moving within the wood structure. The volume of open pores or open porosity of wood may vary between 46% and 80%. This range depends on the grain direction and local structural conditions, for instance, at the end-grain surface wood typically has more pores. Baronas et

al. (2001) explained that the porosity of wood could be defined using the following expression:

$$v_a = 1 - G_m (0.667 + u) \quad (2)$$

$$G_m = \frac{\rho}{\rho_w (1 + u)} = \frac{\rho_o}{\rho_w + 0.883 \rho_o u} \quad (3)$$

where v_a is the wood porosity, G_m wood specific gravity, u wood moisture content, ρ wood density, ρ_o the density of oven-dry wood, and ρ_w the density of water.

The main objective of the study is to gain a more fundamental insight into the role of wood moisture content on its ignition characteristics under fire conditions. This study concerns with the effect of wood moisture content on spontaneous ignition behavior of six kinds of Indonesian wood in order to provide a data base of fire characteristic i.e. ignition time, ignition temperature, end ignition time, end ignition temperature, and charring rate.

2. Experimental Method

The experimental apparatus used in this study was a non- standard truncated heater. Figure 1 shows the schematic layout of the apparatus. This particular instrument was designed in accordance with capable of accommodating samples of up to 25 mm thick if horizontally placed.

It must be pointed out that the studies were mainly concern with the spontaneous ignition of samples. Therefore the spark igniter was not used. A thermocouple on the surface of the sample was used for measurements of temperature history within the test samples. For this study, stainless steel, sheathed, ungrounded junction chromel-alumel thermocouples (0.003 inch out side diameter) were used. The type of thermocouple used for this purpose was K-type made for the temperature range of 95-1260°C. Temperature histories were recorded throughout each experiment at 1 s intervals using a digital data acquisition system (TC-08).

To examine the autoignition of wood, six different species of Indonesian wood (*keruing*, *sono*, *cemara*, *kamper*, *pinus*, and *mahoni*) were tested with a truncated conical heater under irradiance heat flux of 22 kW.m⁻². The wood samples were made into wood blocks with a dimension of 5 cm long, 5 cm wide and 2.5 cm thick, and they were oven dried due to obtain the moisture content variety (0%, 50% and 100%). The experimental procedure consisted of the following steps. Firstly, the sides of the sample except its surface was wrapped in a single layer of aluminium foil in order to minimize the edge effects and to simulate a one-dimensional heat transfer situation. Then, the sample was instrumented with a thermocouple on its surface and then placed horizontally in the sample holder assembly. The samples sitting in the open air and ready to be heated by irradiance heat flux.

The radiant heater was then set to 22 kW.m⁻², which is relevant with temperature of 500°C. When subjected to external heating, wood starts to decompose, giving a mixture of volatile species and a carbonaceous residual or char as products. Flame could be seen to appear in the volatile stream and then flash down to the wood where it persisted on the surface. The ignition time and temperature were recorded as the first appearance of flame and the time of end-ignition was recorded as the disappearance of flame. Meanwhile, the char layer was observed by measuring the thickness of char. The experimental procedures outlined above were

systematically repeated for various combinations of wood moisture content, and they were tested three times at per level of moisture content.

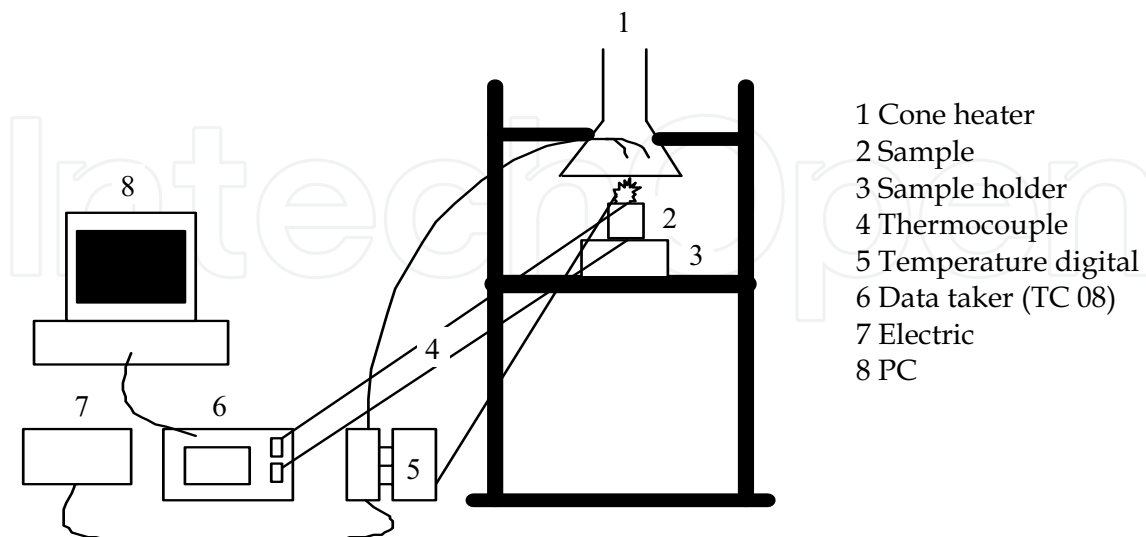


Fig. 1. Schematic layout of non-standard truncated cone

3. Result and Discussions

The fire property of wood samples under external heat flux is illustrated in Figure 2.

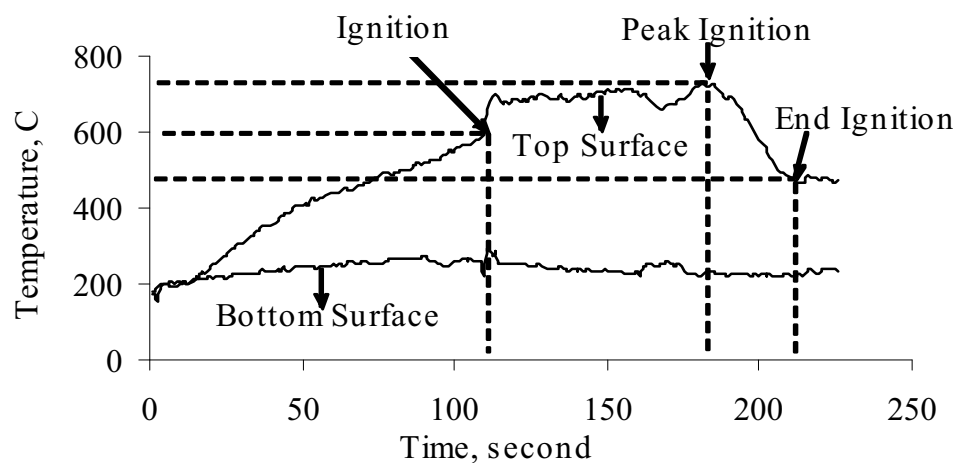


Fig. 2. Temperature profile of wood under external heat flux.

When subjected to external heater, woods start to decompose, produce a volatile matter and carbonaceous residual or char. As can be seen from Figure 2, the spontaneous ignition can be identified by the first sudden jump in the temperature measurement, at this point flaming combustion is achieved when the heat released by gas phase combustion of volatile products provides the heat flux needed for wood degradation and flame spread. After this point, the fire was getting bigger and reached the biggest fire and called as Peak Ignition. Later on the fire gradually weaker and finally the fire disappeared at the end ignition point.

This figure can be divided by three compartments: area between start and ignition called as the growth area, the fully development area between ignition and peak ignition, and the decay period between peak ignition and end ignition.

The results of the experimentally study are presented as histories of fire properties of wood (Ignition temperature, ignition time, end-ignition temperature, end-ignition time, and charring rate) that are illustrated in Figure 3 to Figure 7 and tabulated in Table 1 to Table 5.

Ignition temperature is the temperature of the wood surface at the time of ignition. Figure 3 and Table 1 show the behaviour of ignition temperature of woods under three different moisture content.

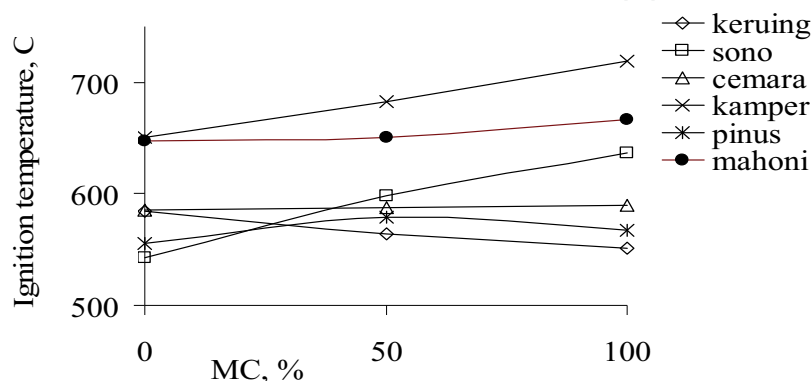


Fig. 3. Ignition Temperature of woods as functions of Moisture Content

MC %	Ignition Temperature, C					
	keruing	sono	cemara	kamper	pinus	mahoni
0	584.76	542.3	585.59	650.9	555.9	646.91
50	564	598.0	587.74	682.72	579.2	650.23
100	551.2	637.1	589.8	719.5	566.9	667.19

Table 1. Ignition Temperature of woods as functions of Moisture Content

As can be seen from Figure 3, most of the curves have linear relationship between ignition temperature and moisture content. It shows that the higher the moisture content, the higher the ignition temperature. *Kamper* wood has the highest ignition temperature for every percent of moisture content. Meanwhile, for 50% of moisture content, the sequences of ignition temperature from the highest to the lowest show the same sequences for 100% of moisture content, as follow: *kamper*, *mahoni*, *sono*, *cemara*, *pinus*, and *keruing*. This ignition temperature sequences also occurred for 0% of moisture content, except for *sono* wood that shows the lowest ignition temperature. Characteristics of wood ignition temperature depend on the species of wood that consist of different percentage of cellulose, hemicellulose, and lignin. These chemical components might affect the behaviour of ignition temperature. This result agrees with Tran (1992), who claims that wood species approximately comprise 50% cellulose, 25% hemicellulose and 25% lignin. Lignin content significantly influences the rate of wood pyrolysis. And Dietenberger (2002) says that hemicellulose typically decomposes between 200-300°C followed by cellulose between 300-350°C, and lignin between 280-450°C.

The effect of moisture content and the kind of wood on end-ignition temperature illustrates in Figure 4 and tabulated in Table 2. End-ignition temperature or extinguish temperature is the temperature when the fire disappear from the sample surface.

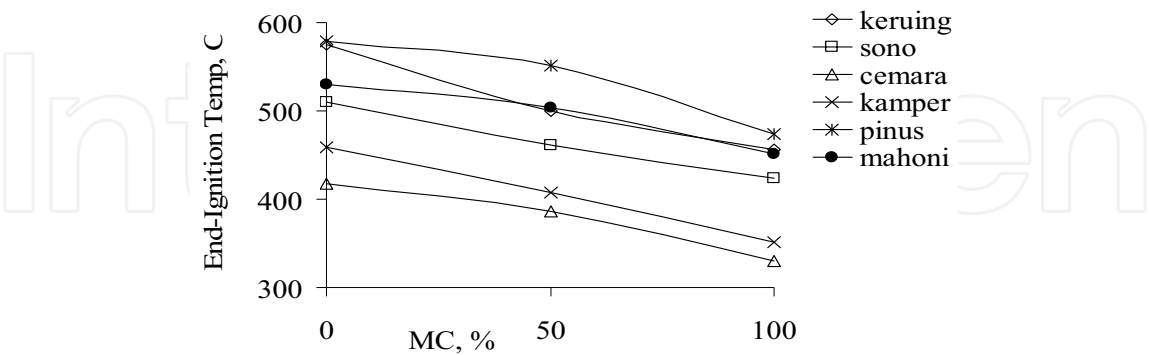


Fig. 4. End-Ignition Temperature of woods as functions of Moisture Content

MC, %	End-Ignition Temperature, C					
	keruing	sono	cemara	kamper	pinus	mahoni
0	575.14	510.6	417.05	458.9	578.2	529.88
50	500.05	460.7	386.39	407.82	551.1	503.5
100	456.03	423.3	329.74	351.25	473.2	451

Table 2. End-Ignition Temperature of woods as functions of Moisture Content

Figure 4 and Table 2 indicate the effects of moisture content of woods on end-ignition temperature. Ignition process of wood is glowing ignition followed by visible fire on the wood surface, and finished by the end of visible fire. In general, *pinus* wood has the highest end-ignition temperature, on the other hand, *cemara* wood has the lowest one. Moreover, the curves indicate that the end-ignition temperature decrease as the increase of moisture content.

The Figure 5 and the Table 3 bellow show the performance of ignition time of woods as a function of moisture content.

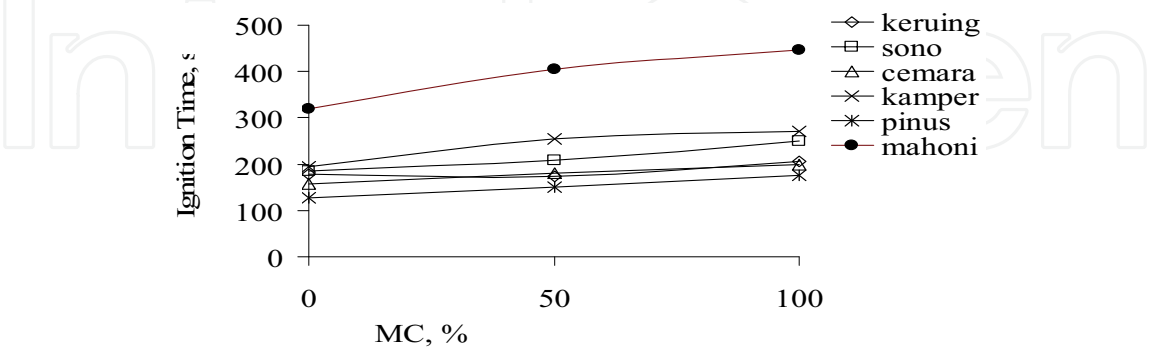


Fig. 5. Ignition Time of woods as functions of Moisture Content

MC, %	Ignition Time, s					
	<i>keruing</i>	<i>sono</i>	<i>cemara</i>	<i>kamper</i>	<i>pinus</i>	<i>mahoni</i>
0	179.33	185.7	157.2	193.67	127.3	319
50	174	208.7	180.2	254	151.3	405
100	205	250.3	198.7	270	176.7	445.67

Table 3. Ignition Time of woods as functions of Moisture Content

As can be seen from Table 3, all specimens tested needed at least about 2 minutes to catch fire at 0% Moisture Content, the longest time to have fire was *mahoni* wood with moisture content of 100%. Ignition time is the minimum time when sample tend to ignite and generate a visible flame or fire under a certain irradiance heat flux. The ignition time increases with the increase of moisture content. This is simply due to the higher the moisture content the more water inside the wood structure, as such, more time to evaporate the water prior ignition process. *Pinus* woods need the shortest time to ignite, it is because *pinus* wood consist more lignin than the other woods, result in the quicker ignition time. The next Figure 6 and Table 4 provide data of end-ignition time under variety of moisture content and wood types.

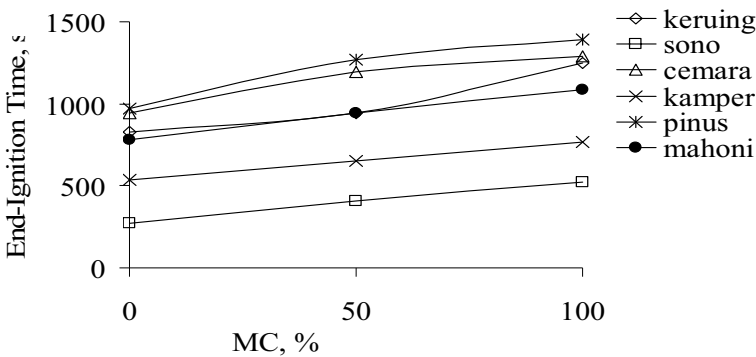


Fig. 6. End-Ignition Time of woods as functions of Moisture Content

MC, %	End-Ignition Time, s					
	<i>keruing</i>	<i>sono</i>	<i>cemara</i>	<i>kamper</i>	<i>pinus</i>	<i>mahoni</i>
0	831.33	272	943.33	538	970	779
50	942.67	404	1191.34	652.3	1268	943
100	1252	523	1288.67	766.7	1394	1086.7

Table 4. End-Ignition Time of woods as functions of Moisture Content

Figure 6 and Table 4 indicate the end-ignition time influenced by moisture content and the kinds of wood. In general the higher the moisture content, the longer the end-ignition time. *Pinus* has the longest time to extinguish, followed by *cemara*, *keruing*, *mahoni*, *kamper*, and *sono*. End-ignition time or extinguish time is the endurance of wood sample under fire condition. This fire endurance depends on the charring rate of wood. It can be noted that the longer the charring rate, the longer the end-ignition time. The endurance of fire on the sample surface also influenced by the oxygen availability, both oxygen in the sample structure and oxygen from environment. It means that the more the oxygen, the longer the

fire on the sample. The more oxygen in the sample structure, the more porous the sample, as such the lower the sample density. Figure 7 and Table 5 give the charring rate occurrence under different moisture content and wood species.

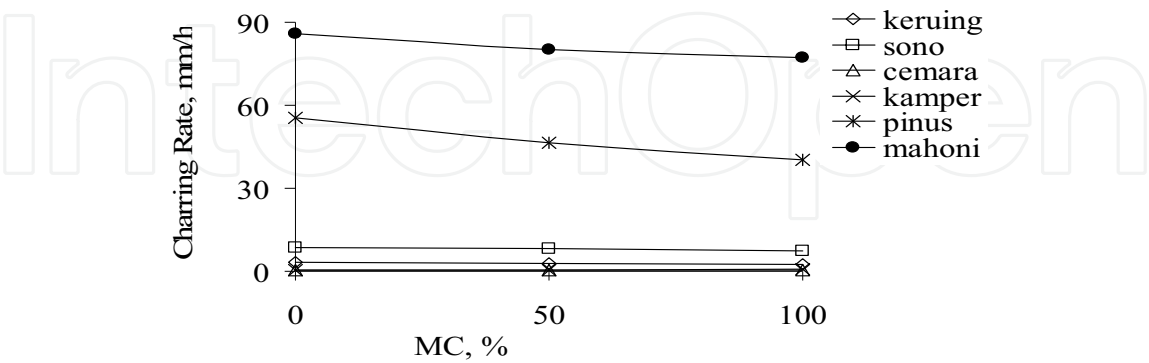


Fig. 7. Charring Rate of woods as functions of Moisture Content

MC, %	Charring Rate, mm/h					
	<i>keruing</i>	<i>sono</i>	<i>cemara</i>	<i>kamper</i>	<i>pinus</i>	<i>mahoni</i>
0	3.21	8.7	0.32	0.41	55.4	85.72
50	3	8.09	0.31	0.55	46.4	80
100	2.62	7.27	0.32	0.66	40.2	77.34

Table 5. Charring Rate of woods as functions of Moisture Content

Figure 7 and Table 5 show the charring rate of all kinds of wood under various level of moisture content. The charring rate of wood refers to the dimensional rate (mm/h), at which wood change to char. The pyrolysis behaviour of wood as a charring fuel leaves relatively significant amounts of carbonaceous residue (char) when it burns. The porous residue, in turn, alters the heat and mass transfer processes within the solid. For every value of moisture content, *mahoni* wood has the highest rate of char formation; followed by *pinus* wood, *sono* wood, and *keruing* wood. On the other hand *kamper* wood and *cemara* wood have the lowest charring rate. The differences of wood charring rate are affected by the differences of wood characteristics such as density, permeability, anatomy, and chemical composition. Compared with Figure 6, Figure 7 gives inconsistent results, the sequence of charring rate should be relevant with the sequence of end-ignition time. The only consistent result was found for *keruing* wood and *kamper* wood.

4. Conclusions

A typical virgin wood sample is made of solid cells strongly bounded but with evident cavities (slits), which seem to continue along the grain direction. After being exposed to external heat and formation of the char layer, the natural porosity of the material allows the volatile release and no major morphological changes occur within the virgin layer. However, the cell structure practically does not exist within the char layer. The cross sectional image of the sample suggests that the sample have larger cavities with thinner cell

walls in its char layer. At high heat flux actuation, the char layer almost completely lost its own distinctions, at lower heat fluxes the char layer showed distinct similarities with virgin layer. This suggests that the structure of the sample and its transformation during the re-ignition process is a function of the heat flux.

In the present paper, the fire properties of autoignition of wood samples have been experimentally conducted. The results of the present study indicate that in general ignition temperature, ignition time, end-ignition temperature, end-ignition time, and charring rate of wood based materials are functions of their moisture content and their chemical composition. In general, it can be indicate that fire properties of wood are affected by moisture content, chemical components, and density. More properly experimental equipment such as standard cone calorimeter should be applied in order to get the consistent results.

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