EFFECTS OF POROSITY ON RE-IGNITION CHARACTERISTICS OF WOOD

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ABSTRACT

This experimental study is part of a major study on re-ignition characteristics of wood-based materials. The main objective of this study was to investigate the role of wood porosity on its re-ignition characteristics. For this purpose, 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}. Experiments were conducted in a modified mass-loss cone calorimeter equipped with a water spray system. Results of this study were consistent with our 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}.

Keywords: Re-ignition, porosity, wood, extinction, combustion.

INTRODUCTION

Wood-based materials often constitute the bulk of fuel load in building fires. The growth of such fires may be interrupted or terminated in various ways. The common practice is to extinguish the burning wood-based objects with water using an automatic sprinkler system or via the fire brigade action. However, the extinguished wood-based object may still receive a substantial amount of radiative energy from the ceiling layer, hot walls and other burning objects. As a result, the extinguished object may re-ignite. Here, re-ignition refers to the reappearance of a flame in the volatile gas stream evolving from the object. Re-ignition of charring fuels like wood is a complex phenomenon involving the interaction of various physical (e.g. porosity), thermal and chemical processes. The complexity is partly due to existence of the significant amounts of carbonaceous char residue, which alters the heat and mass transfer processes within the solid.

Re-ignition phenomenon is of particular interest as a fundamental combustion problem, surprisingly, only a limited number of experimental studies have provided information on re-ignition problem (Usui, 1950; Depew *et al*., 1973; Takahashi, S., 1982, 1984a, 1984b, 1986; Moghtaderi *et al*., 1997, 1998, 2000, 2002, and Poespowati *et al*., 2001). The key parameters, which control the re-ignition mechanism on charring solid fuels, have been identified as structural properties of fuel (*e.g.* porosity), the percentage of pre-burn, and the amount of water applied in the extinguishment phase. However, detailed studies on the role and relative importance of key structural parameters (porosity) were not performed.

Depew *et al.* (1973) performed experiments on a cellulocic object exposed to external radiation and extinguished by water droplets. They quantified the re-ignition time of the fuel surface. Their work was mainly concerned with the re-ignition phenomenon in wild-land fires. Other investigators (Takahashi 1982, 1984a, 1984b, 1986) conducted a series of theoretical and experimental studies based on Usui's (1950) data to obtain a relationship between the re-ignition time and water content of wood embers under a wider range of heating conditions. Usui (1950) carried out a series of experiments on re-ignition phenomenon of wood cribs extinguished by a water spray. The combined experimental and numerical studies conducted by Moghtaderi and co-workers (1997, 1998, 2000, 2002) on re-ignition of charring and non-charring solid fuels showed that the re-ignition characteristics of charring and non-charring materials are significantly different. Rawet *et. al*. (1996) studied the effectiveness of six water-based extinguishants on preventing the re-ignition of wood under forest fire conditions. However, no rational framework was established to quantify the effects of controlling factors, also no attention was given to the thermal, physical, and chemical processes associated with the solid or gas phases under fire conditions.

We have recently (Poespowati *et al*., 2001) studied the role of porosity on the re-ignition characteristics of solid fuels using a surrogate ceramic-based material doped with liquid fuel. The surrogate material was used because it had a well-defined porous structure similar to that of wood and the fact that, unlike wood, its porosity did not change during the re-ignition process. This allowed us to study the porosity in isolation from other controlling parameters, particularly, char oxidation and its resultant structural transformations. Through our studies we found that the re-ignition delay time was significantly affected by the ceramic porosity. The higher were the porosity levels of the surrogate ceramic, the longer were the re-ignition delay times. As expected, the re-ignition delay times of surrogate samples were also found to be inversely proportional to the external heat flux. In the present work, we extended our previous studies and investigated the re-ignition of several wood species exposed to external radiation. The main objective was to gain a more fundamental insight into the role of wood porosity on its re-ignition characteristics under fire conditions and to find out whether the results are consistent with those of our past studies.

EXPERIMENTAL SET-UP, METHODS AND TECHNIQUES

Measurements of weight loss and temperature were carried out in the set-up schematically shown in Figure 1. The set-up consisted of a mass-loss cone calorimeter fitted with a shutter for its heating element, a water spray system, a cooling unit, a gas exhaust manifold, a data acquisition system, and several additional items including a waterproof shield for the load-cell, a modified sample holder, and a tray.

The spray system comprised a nozzle, a set of valves, piping, and fittings. The nozzle was a full cone BLM 4-90 nozzle manufactured by Delavan, with an effective angle of about 90^{o}. To facilitate the water application and to minimize the blockage of the radiant heat by the nozzle, the distance between the nozzle tip was kept at 11 cm. During each test the nozzle flow was held constant at 150 ml.min^{-1} by maintaining a constant water pressure. No attempt was made to measure the drop size distribution. However, according to information supplied by the manufacturer, at an operating pressure of 300 kPa the volume median diameter of the drops was 850 μm.

Temperature measurements were carried out using 0.003 inc. diameter chromel-alumel (K type) thermocouples, and the temperature histories were recorded throughout each experiment at 1 s intervals using a digital data acquisition system. For temperature measurements, samples were instrumented by several thermocouples to measure the surface, back and at least one interior temperature.

The distance between the surface of sample and the cone frustum was regularly checked and maintained at 25 mm. All samples were positioned in the sample holder and they were tested in the horizontal orientation. To minimize the edge effects and to simulate a one-dimensional heat transfer situation, the sides and base of the specimen were wrapped in aluminium foil.

The experimental procedure involved the following steps. At first, the sample was instrumented with thermocouples and then placed in the sample holder. The radiant heater was then set to the desired value and the sample was then exposed to the external radiation by placing the sample holder under the radiant heater. No external ignition source was used; instead spontaneous ignition was allowed to occur. Once a stable flame appeared at the surface of the specimen, it was allowed to burn under the conditions selected until the sample weight diminished to a pre-determined value. The application of the water spray was then started in order to extinguish the flame. At the same time measurement of the re-ignition time was started. The water spray was left on for a selected period of time (5, 10 or 15 s), which was much longer than the time required for extinguishment. The specimen was kept under the external radiation until the specimen re-ignited. Re-ignition was judged to have occurred when a stable flame reappeared at the sample surface. This procedure was repeated for various combinations of radiant flux, water application rate and pre-burn which is defined as: $\%PB = (M_0 - M)/M_0$, where M_0 is the initial sample weight and M is the weight just prior to water spray application.

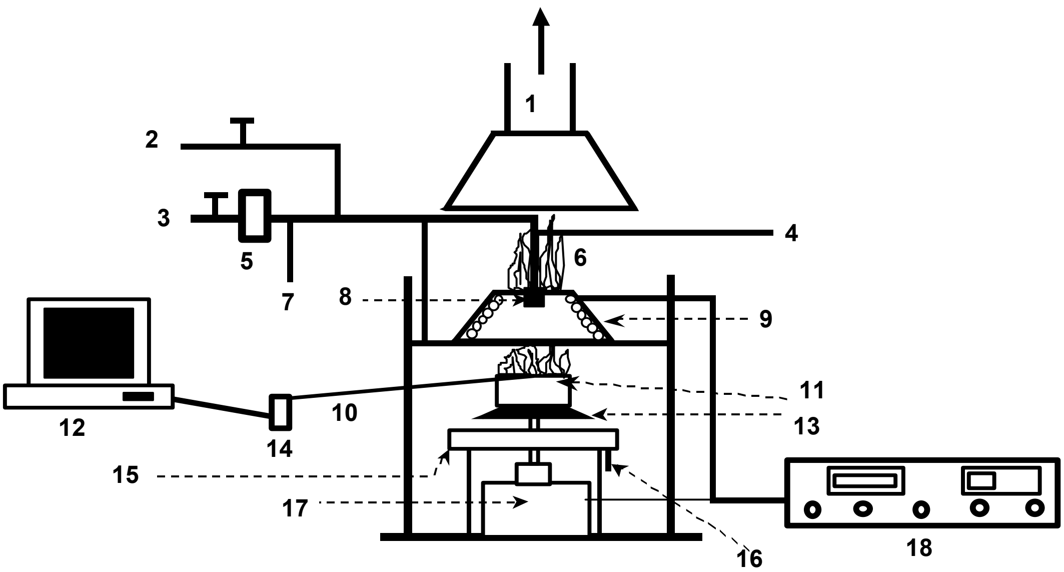

Figure 1: *Experimental set-up (not to scale)*

1. Exhaust system	7. By pass water	13. Shield
2. Cooling water	8. Nozzle	14. Terminal
3. Spray water	9. Cone heater	15. Tray
4. Drain water	10. Thermocouple	16. Drain water
5. Flow meter	11. Sample holder	17. Load cell
6. Fire	12. PC	18.Cone controller

Experiments were conducted on three wood species: Western Red cedar, Radiata pine, and Red River gum of which Western Red cedar, and Radiata pine are softwood species while Red River gum is a hardwood species. Mercury Porosimetry was used to determine the pore size distribution of these woods. The porosities of virgin samples were measured as 74.5864%, 57.96447%, and 34.69277% for Western Red cedar, Radiata pine, and Red River gum, respectively. All samples were 100 mm square as required for testing in the mass-loss cone calorimeter and the thicknesses of all samples were 20 mm. Their grain was perpendicular to the incident heat flux. To eliminate the effect of moisture content, all samples were oven-dried at 105^{o}C to a constant mass and then stored in a desiccator.

RESULTS AND DISCUSSION

Figure 2 illustrates the result of the surface temperature history of a typical Radiata pine sample as a function of external heat flux. This particular graph corresponds to a 10 s water application time.

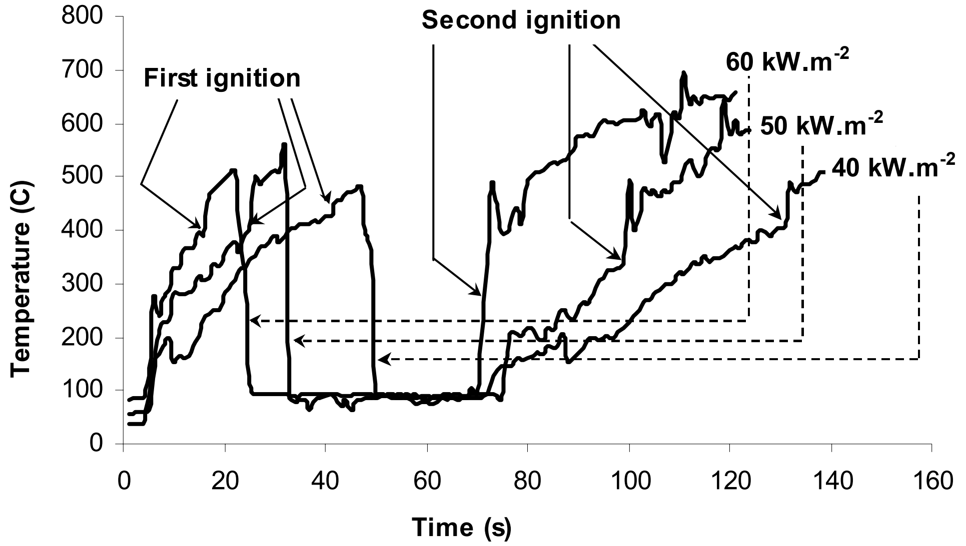

Figure 2: *Surface temperature versus time for Radiata Pine exposed to different level of heat flux, with 10s of water time application.*

As can be seen from Figure 2, the first spontaneous ignition can be identified by the first sudden jump in the temperature measurement. The temperature drop after the first ignition and appearance of the flame, is essentially due to the cooling effect of the water droplets of which some penetrate into the sample, some form a thin layer on the sample surface, and some run-off from the edges. Once the application of water is stopped, evaporation of water begins from the top layer. This stage can be identified by a relatively low temperature plateau region on the graphs shown in Figure 2. In this stage, the incident energy due to the external heat flux is essentially consumed to evaporate the water rather than to increase the surface temperature. At the end of water layer evaporation stage more and more energy gets to the sample itself and as a result its temperature starts to rise allowing pyrolysis to proceed again. As soon as enough pyrolysis products (i.e. volatiles) accumulate in the boundary layer surrounding the sample surface, the second ignition, which is referred here as re-ignition will occur. This usually corresponds to a surface temperature close to that just prior to the application of water (see Figure 2). The influence of the heat flux on re-ignition time is quite significant. As illustrated, the re-ignition delay time decreases with the increase in the external heat flux. The re-ignition time for Radiata pine under the heat flux levels of 40, 50, and 60 kW.m^{-2} were 90 s, 74 s, and 56 s, respectively. It was also found that the higher the external heat flux, the lower the delay time correspond to the first ignition time.

The effect of different water application times on the surface temperature profile is shown in Figure 3 for Radiata pine exposed to the heat flux level of 40 kW.m^{-2}. Clearly, for longer water application times the re-ignition delay time is longer than those correspond to the shorter application times. This is simply due to the fact that for longer application times a larger quantity of water will accumulate in the sample and on its top surface and, as such, more time is needed to evaporate the water. Similar behaviour was observed for samples of other wood species although their exact values of re-ignition delay time were different.

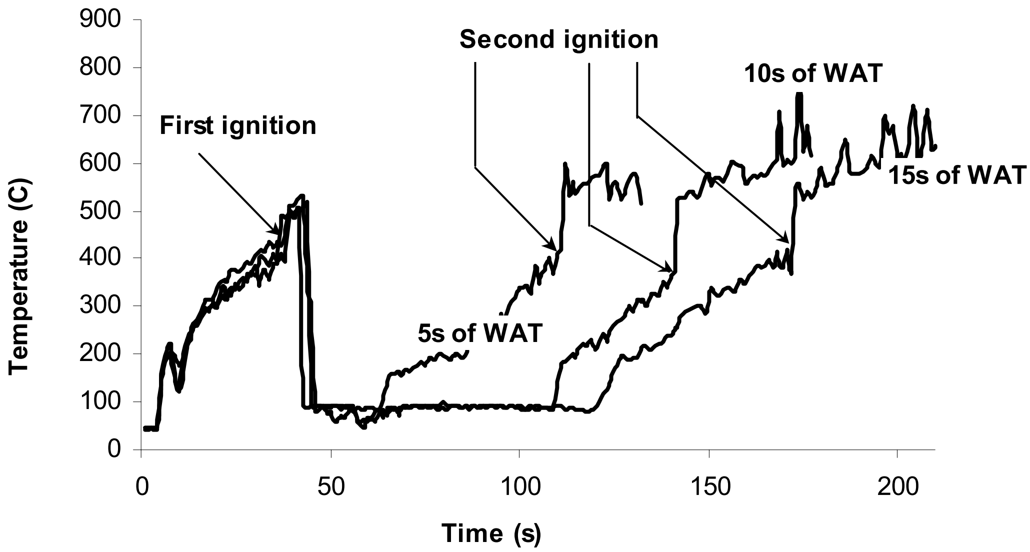

Figure 3: *Surface temperature versus time for Radiata Pine exposed to a heat flux level of 40 kW.m^{-2} at different time of water time application.*

Figure 4 depicts the influence of wood types (implicitly the influence of wood sample porosity) on the re-ignition behaviour, the evaporation time, and the recovery time. These results were obtained at an external heat flux of 50 kW.m^{-2} and a water application time of 15 s. The values of the first ignition delay time, second ignition delay time (i.e. re-ignition delay), evaporation time, and recovery time of the same types of wood extracted from Figure 4 are tabulated in Table 1.

Table 1: *First Ignition time, second ignition time, evaporation time, and recovery time of wood samples subjected to the 50 kW.m^{-2} of heat flux and 15 s of water application.*

Wood type	1st ignition time, s	2nd ignition time, s	Re-ignition time, s	Evaporation time, s	Recovery time, s
Western Red cedar	21	125	99	25	62
Radiata pine	30	118	83	39	39
River Red gum	48	126	73	60	7

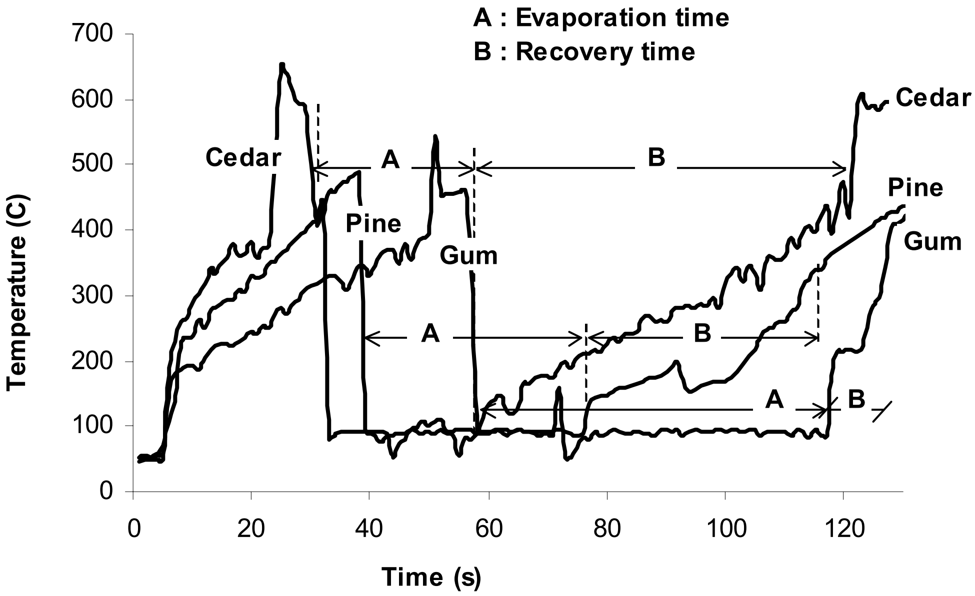

Figure 4: *The influence of wood porosity on the re-ignition behaviour, evaporation time, and recovery time under 50 kW.m^{-2} of heat flux and 15 s of water application.*

From Figure 4 and Table 1, it can be concluded that evaporation time for more porous wood sample was shorter than the evaporation time of less porous ones. Inversely, the more porous wood sample, took more time to recover. This phenomenon can be explained in terms of the characteristic of the porous structure. With the same water application time, the sample with a higher porosity level will absorb more water into its structure and, hence, a less quantity of water will stay on the sample surface. Therefore, less time is required to evaporate the water layer on the sample surface. On the other hand, it will require more time to evaporate water content in the sample structure.

The behaviour of the first ignition time of the three woods sample named before under different level of external heat flux is provided in Figure 5. As Figure 5 indicates, it is easier to get the first ignition for wood samples having a higher porosity level. The main reason for such behaviour is that as higher porosity levels volatiles can escape faster from the interior of the solid fuel and, as such, it would take a shorter time period to reach to the lower flammability limit of the fuel/air mixture in the boundary layer around the surface. Consequently, ignition occurs in a relatively shorter time-scale. As can be seen from this figure the first ignition delay time for Radiata pine and Western Red cedar are fairly close, but they are both quite different from that of the River Red gum. Such differences can partly be assigned to the fact that River Red gum is classified as hardwood while Western Red cedar and Radiata pine are classified as softwood. Generally, soft- and hardwoods have different characteristics in terms of their chemical structures. In particular, hardwoods have a lower percentage of lignin ($C_{10}H_{11}O_2$) than softwoods and, therefore, their ability to form a highly porous char layer at the onset of the first ignition is very limited. This would imply that around the time of the first ignition, the overall porosity of a typical River Red gum sample is almost the same as its virgin one, which is significantly less than those of softwood species anyway. Consequently, River Red gum exhibits relatively long ignition delays simply because of its lower porosity.

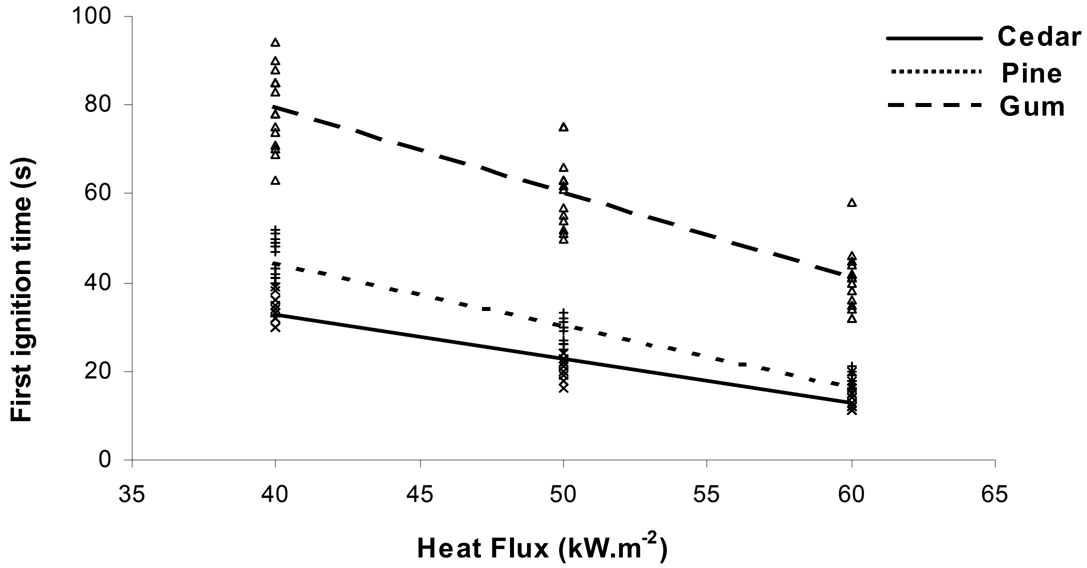

Figure 5: *First ignition time of Western red cedar, Radiata pine, and River red gum under different level of irradiance heat flux.*

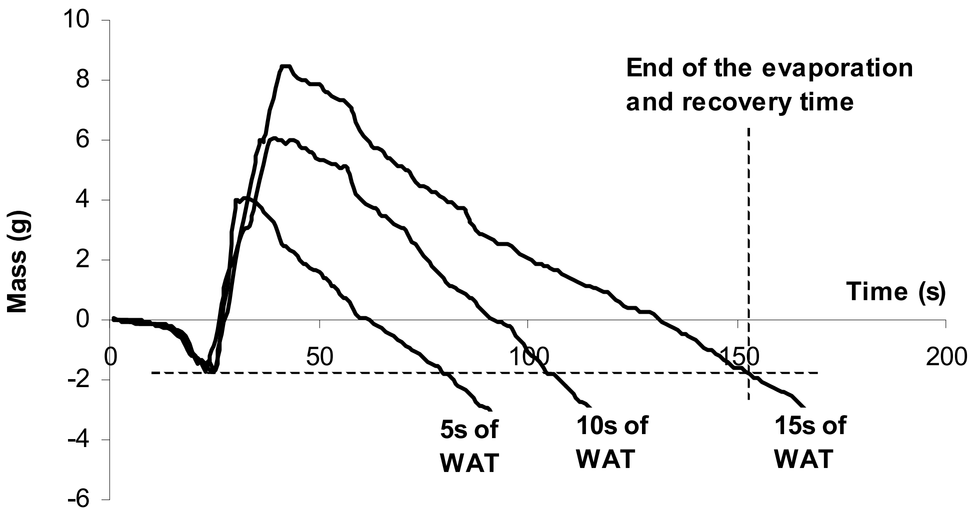

Figure 6: *Mass loss of Western red cedar exposed to a heat flux level of 40 kW/m^2.*

The influence of water application time on the mass loss behaviour of Western Red cedar under the heat flux level of 40 kW.m^{-2} is illustrated in Figure 6. In this figure the weight of the sample has been tarred off. Thus, a zero mass refers to the initial weight of the sample. As Figure 6 shows, as soon as the heat-up phase begins and material starts to pyrolyse the mass of wood sample gradually decrease. After water application the sample starts to gain weight as a result of water applied. Once the water application is stopped and evaporation begins, weight loss is observed again. But in the greater part of this phase the material temperature is not high enough to cause pyrolysis. Therefore, the observed weight loss is primarily due to evaporation of water. However, once the water has completely evaporated and sample weight returns to a value similar to that prior to the application of water, then the material weight loss begins again. The points corresponding to this phenomenon have been marked on Figure 6. Clearly, the overall re-ignition time increases as the water application time is increased simply because there is more water to be evaporated. The higher the water application time, more water spreads over the surface and penetrate into the interior of the sample and, as a result, takes longer time to evaporate. Similar behaviours were observed for other samples.

The measured re-ignition times of the three wood species have been summarised as a function of water application time (at a heat flux of 40kW.m^{-2}) in Figure 7 and as a function of external heat flux (at a water application time of 15 s) in Figure 8.

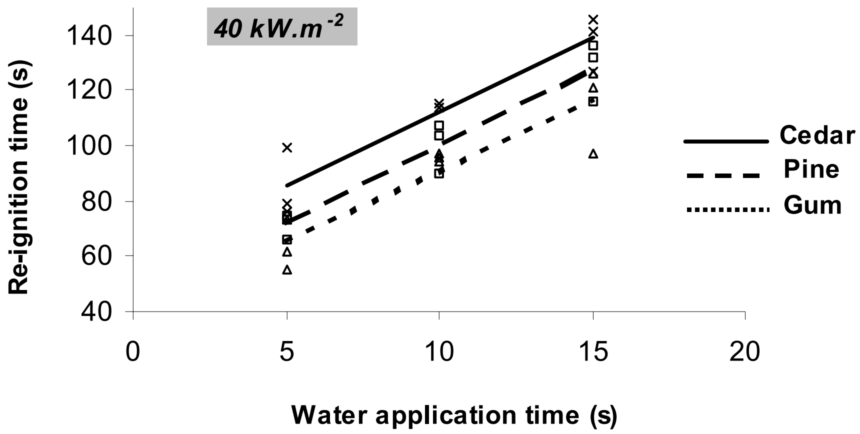

Figure 7: *Re-ignition time as a function of water application time and porosity at different level of heat flux.*

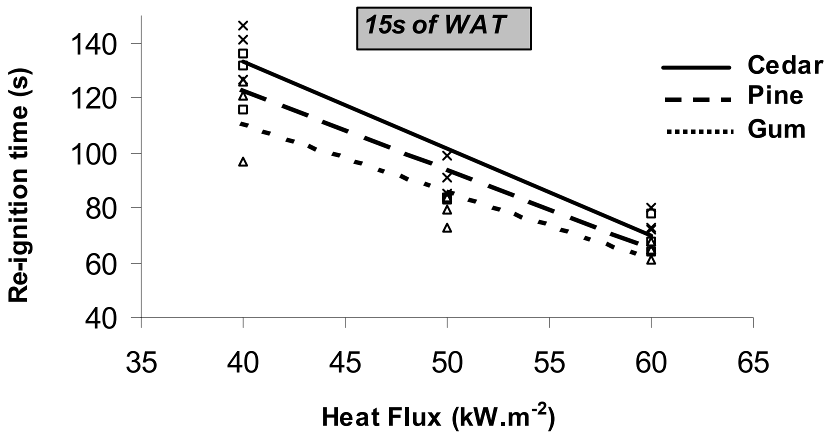

Figure 8: *Re-ignition time as a function of heat flux and porosity at different time of water application.*

Figure 7 indicates that for the same water application time, the re-ignition time is inversely proportional to the porosity of samples. As discussed before, the physical structure of high porosity samples allows them to absorb more water, which implies a longer recovery time. Figure 8 also indicates that there is an inverse linear relationship between re-ignition delay time and the external heat flux. This figure also shows that at a given level of heat flux, the re-ignition times of samples having high levels of porosity are generally higher than those of less porous samples. This can be explained in terms of the interaction between the hot porous structure of the samples and cold-water droplets. Samples with high porosity levels allow the water droplets to penetrate more deeply into their structure. As a result, the cooling process affects a larger portion of the sample. Therefore, at a given rate of heat flux, the sample needs a longer time to get back to its original conditions. In addition, the samples with lower porosity levels generally have higher thermal conductivity and, as such, they are able to regain their initial conditions quicker than samples with a high degree of porosity. In the sample with low thermal conductivity, intensive local cooling will be produced by the water droplets, result in longer time to recovery process and, therefore, the longer the re-ignition time.

The effect of %PB on re-ignition characteristics of wood species were also investigated in this study and the typical results for Radiata pine are shown in Figures 9 and 10.

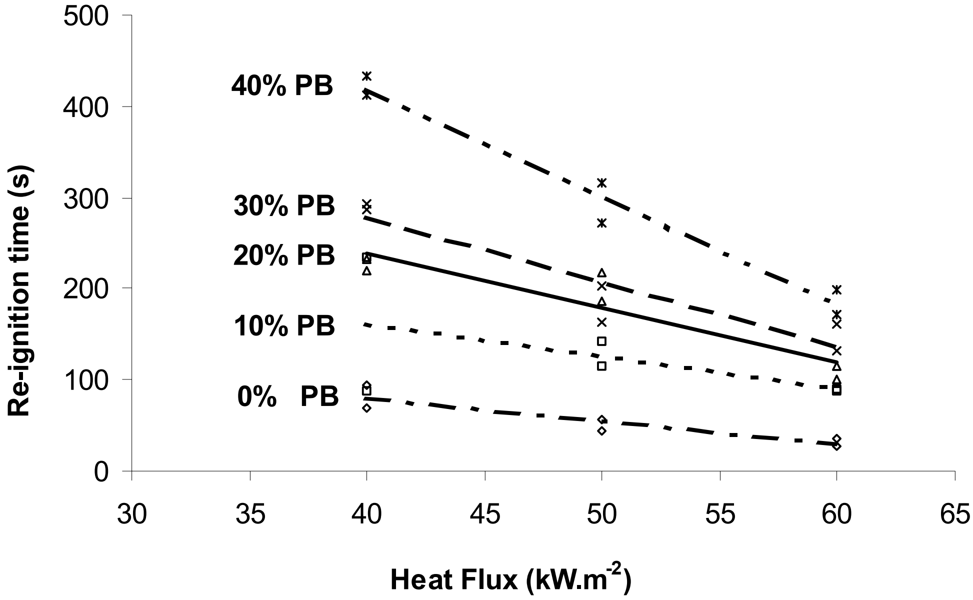

Figure 9: *Re-ignition time of Radiata pine as a function of irradiance heat flux for different percentages of pre-burn.*

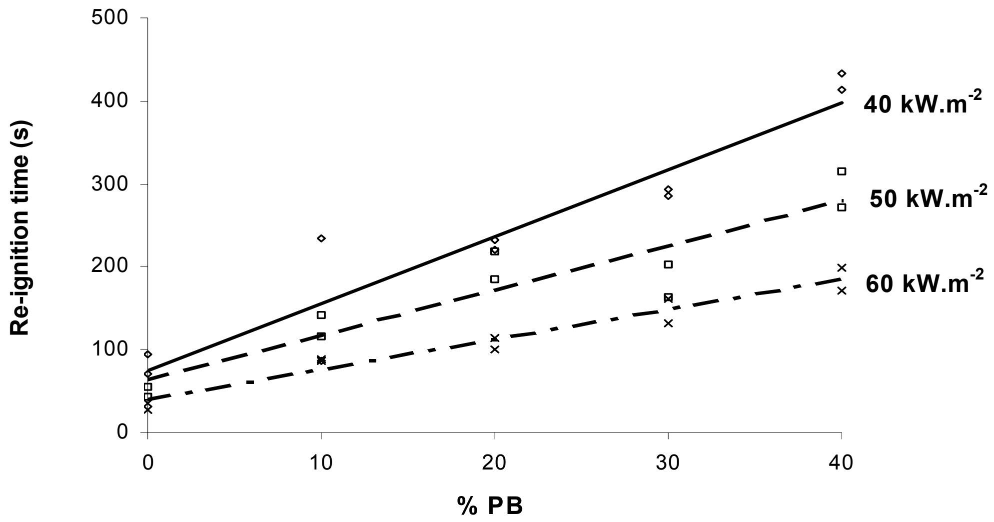

Figure 10: *Re-ignition time of Radiata pine as a function of % PB for different level of irradiance heat flux.*

Clearly, there is a linear relationship between the re-ignition time and the %PB. This can be explained in terms of the role played by the char layer during the whole process. Char essentially acts as an insulator and prevents heat to be easily conducted into the material. Thus, it would be more difficult to conduct heat into a sample with a higher percentage of pre-burn because the sample simply has a thicker char layer. In addition, there is less virgin material left in a sample with higher %PB. Furthermore, due to the highly porous structure of the char layer, a sample with high %PB would absorb more water. Consequently, one would expect that the re-ignition of a highly burnt sample (high %PB) to take place at relatively longer delay times as a result of the above-mentioned effects due to the char layer.

CONCLUSIONS AND FUTURE WORK

The results of experimental investigations of the re-ignition characteristics of wood species are presented in this paper. It was shown that the re-ignition characteristics of wood are greatly affected by wood porosity, which influences the evaporation and recovery times. The re-ignition delay time, in particular, was found to have linear relationships with porosity and the water application time and an inverse linear relationship with the heat flux. The %PB was also found to play a major role on the re-ignition phenomenon through the influence that it has of the porosity of the fuel. Qualitatively, very similar behaviours were exhibited by ceramic-based surrogate samples that we studied in our previous work. We are now in the process of making a comprehensive analysis of both sets of results in order to quantify the similarities and differences. The result of this study will be presented in our future publications.

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