

EFFECTS OF POROSITY ON RE-IGNITION CHARACTERISTICS OF A SURROGATE MATERIAL

T. Poespowati, B. Moghtaderi, B. Z. Dlugogorski, and E. M. Kennedy

Department of Chemical Engineering, The University of Newcastle

AUSTRALIA

ABSTRACT

This study is part of a larger project which aims at studying the re-ignition behaviour of charring solid fuels under fire conditions. The main objective of this part of the work was to investigate the role of material porosity on the re-ignition characteristics of the fuel. For this purpose, experiments were carried out on a set of surrogate ceramic samples to de-couple the pyrolysis and combustion processes from those associated with heat transfer. The surrogate samples were made out of magnesia silica ceramic with porosity levels of 72.9%, 53.5%, and 35%. Experiments were conducted in a modified cone calorimeter over a range of heat fluxes between 40 to 60 kW/m². The re-ignition delay was found to be significantly affected by the material porosity. The higher the porosity, the longer the re-ignition delay time. For samples having the same porosity level, the re-ignition delay time was primarily a function of sample thickness and the external heat flux. Thicker samples generally showed shorter re-ignition delays. The results of this study will be used in future work to quantify the impact of porosity on the re-ignition behaviour of real samples.

Keywords: Re-ignition, porosity, water spray, cone calorimeter.

INTRODUCTION

This paper is concerned with re-ignition phenomenon and, in particular, with the impact of material porosity on the re-ignition behaviour of charring solid fuels. Here, re-ignition refers to the re-appearance of a stable flame at the surface of a solid fuel after a water spray has extinguished it. The interest in water sprays originates from the fact that water is the most widely used extinguishing agent owing to its availability, low cost, and negligible contaminating effects. Such a phenomenon may occur if an extinguished solid object keeps receiving radiative energy from the ceiling layer, hot walls and other burning objects. Re-ignition of charring fuels is a complex phenomenon involving the

interaction of various physical, thermal and chemical processes. Complexity is partly due to the fact that charring fuels, such as wood, leave a carbonaceous residue (char) behind once they are exposed to sufficiently high heat flux levels. The porous residue, in turn, alters the heat and mass transfer processes within the solid.

The re-ignition phenomenon is of particular interest not only as a fundamental combustion problem, but also as a serious and sensitive fire safety issue. Surprisingly, very little information is currently available on this topic and there are only a handful of papers¹⁻⁹ available in the open literature. Among these, Depew et al.¹ studied the response of a cellulosic object exposed to external radiation and impinged by water droplets. They also quantified the recovery time of the surface, which was defined as the time required for re-ignition under constant radiative heat flux following a burst of water. However, no rational framework was established to quantify the effects of controlling factors, such as the fuel type and the amount of pre-burn. In addition, this work was mainly concerned with the re-ignition phenomenon in wild-land fires rather than buildings.

Usui² conducted a series of experiments on re-ignition phenomenon of wood cribs extinguished by a water spray. Later Takahashi³⁻⁶ carried out a series of theoretical and experimental studies based on Usui's data to obtain a relationship between the re-ignition time and water content of wood embers under a wider range of heating conditions.

Rawet et al.⁷ studied the effectiveness of six water-based extinguishants on preventing the re-ignition of some Australian wood species under forest fire conditions. No attention was given to the thermal, physical, and chemical processes associated with the solid or gas phases under such conditions.

In some recent works by the present authors⁸⁻⁹ combined experimental and numerical studies have been performed on re-ignition of charring and non-charring solid fuels extinguished by a water spray. It was shown that the structural differences between charring and non-charring materials result in significantly different re-ignition characteristics. These studies, which remain the most detailed studies on the matter to date, were quite successful in identifying fuel porosity and char oxidation as the key parameters of the re-ignition mechanism for wood-based materials. However, due to the lack of suitable experimental methods, detailed studies on the role and relative importance of such key parameters were not carried out.

The main objective of the present study was to gain a more fundamental insight into the role of fuel porosity on the re-ignition characteristics of wood-based (charring) materials. To address the shortcomings associated with earlier experimental techniques, the porosity effect has been de-coupled from the combustion process by employing a surrogate material (magnesia silica ceramic) instead of wood samples. The present paper summarises the results of this preliminary study on the surrogate material. In the next phase of work, the authors will relate these preliminary results to the characteristics of wood-based materials by correlating their thermal properties.

EXPERIMENTAL

Apparatus, methods and techniques

A modified cone calorimeter equipped with a water spray system was utilized in this study. The schematic of the apparatus, which is essentially similar to a cone calorimeter without its gas analysers, is shown in Figure 1. Extinguishment was achieved by introduction of water droplets through the

spray system that consisted of a nozzle and a set of valves, piping and fittings. To facilitate the water application and to minimise the blockage of the radiant heat by the nozzle, the distance between the sample and the nozzle tip was kept at 7 cm. The flow rate of water was 100 mL/min and the water losses during application were between 47% to 69%. The water application was initiated when the surface reached a stable temperature (480^oC for thick samples and 600^oC for thin samples). Temperature measurements were carried out using thermocouples. Three stainless steel, sheathed, ungrounded chromel-alumel thermocouples (0.003 " o.d.) were used. They were press fitted into the holes which were equally spaced between the surface and the bottom of the sample.

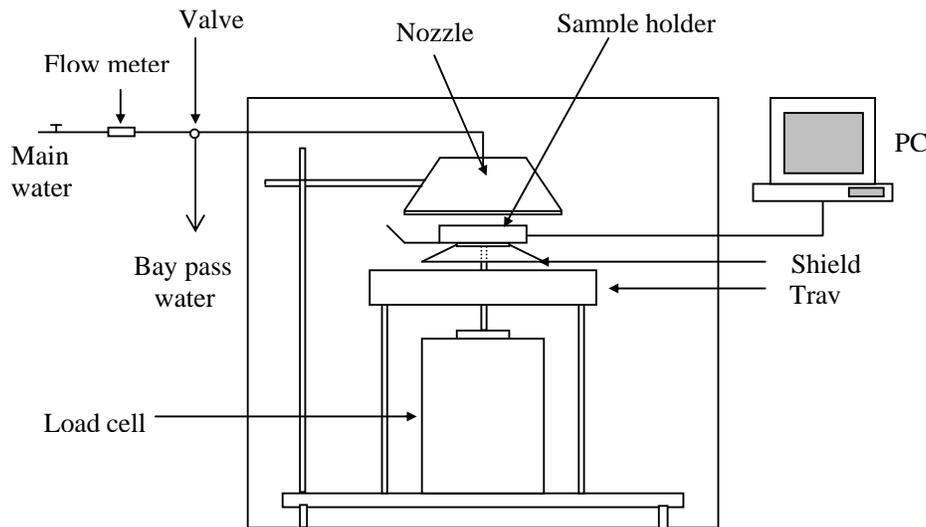


Figure 1: Schematic of the experimental apparatus.

All samples were positioned in the sample holder and they were tested in the horizontal orientation. To minimise the edge effects and to simulate a one dimensional heat transfer situation, the sides and base of the specimen were wrapped in aluminium foil. After the sample was heated to the desired temperature, water spray was applied for a pre-determined period of time (5, 10 or 15 s). The sample was then left under the cone heater to regain its initial surface temperature. The interval between the time at which the water spray was applied and the time at which the temperatures reached their original values was considered as the re-ignition time for the surrogate samples. The temperature histories were recorded throughout each experiment at 1 s intervals using a digital data acquisition system. Experimental data were collected for different samples (i.e. different porosity levels) and different combinations of parameters such as heat flux and water application time. Samples with three porosity levels were examined to quantify the impact of fuel porous structure on re-ignition behaviour. The effect of heat flux on the re-ignition behaviour of samples, at constant water flow rate and sample porosity, was determined over a range of heat fluxes between 40 kW/m² to 60 kW/m².

Materials

Experiments were conducted on samples of a magnesia-silica-based ceramic with three different open porosity levels of 35% (Isomag 110R), 53.5% (Isomag 70), and 72.9% (Isomag 45). These porosity levels are consistent with those of wood-based materials. Samples were cut to a size of 100 × 100 mm with two different thicknesses of 12 and 25 mm. Table 1 provides a summary of the thermophysical properties (including the effective thermal conductivity) of the magnesia silica ceramic samples.

Table 1: Specification of magnesia silica ceramic.

N a m e	Isomag 45	Isomag 70	Isomag 110R																								
Porosity	72.9 %	53.5 %	35 %																								
Density	690 ± 7% kg/m ³	1202 ± 7% kg/m ³	1650 kg/m ³																								
Max service temperature	1090°C	1050°C	1000°C																								
Continuous service temp	1000°C	1000°C																									
Cold crushing strength	3.8 MPa	15.1 MPa																									
Hot compressive strength at 5% strain	4.4 MPa at 500°C	18 MPa at 300°C 17 MPa at 500°C																									
Flexural strength	3.3 MPa	13.1 MPa	20.7 MPa																								
Effective Thermal conductivity	195°C : 0.17 W/m.K 315°C : 0.19 W/m.K 600°C : 0.25 W/m.K	195°C : 0.23 W/m.K 315°C : 0.24 W/m.K 600°C : 0.31 W/m.K	0.20 W/m.K																								
Permanent shrinkage	<table border="0"> <tr> <td>Linear</td> <td>Thickness</td> </tr> <tr> <td>300°C : 0.04%</td> <td>0.17%</td> </tr> <tr> <td>500°C : 0.07%</td> <td>0.22%</td> </tr> <tr> <td>750°C : 0.21%</td> <td>0.47%</td> </tr> <tr> <td>900°C : 0.72%</td> <td>3.59%</td> </tr> <tr> <td>1000°C: 2.00%</td> <td>3.60%</td> </tr> </table>	Linear	Thickness	300°C : 0.04%	0.17%	500°C : 0.07%	0.22%	750°C : 0.21%	0.47%	900°C : 0.72%	3.59%	1000°C: 2.00%	3.60%	<table border="0"> <tr> <td>Linear</td> <td>Thickness</td> </tr> <tr> <td>300°C : 0.02%</td> <td>0.08%</td> </tr> <tr> <td>500°C : 0.07%</td> <td>0.18%</td> </tr> <tr> <td>750°C : 0.13%</td> <td>0.42%</td> </tr> <tr> <td>900°C : 0.64%</td> <td>1.03%</td> </tr> <tr> <td>1000°C: 1.64%</td> <td>4.00%</td> </tr> </table>	Linear	Thickness	300°C : 0.02%	0.08%	500°C : 0.07%	0.18%	750°C : 0.13%	0.42%	900°C : 0.64%	1.03%	1000°C: 1.64%	4.00%	8 % linear at 700°C
Linear	Thickness																										
300°C : 0.04%	0.17%																										
500°C : 0.07%	0.22%																										
750°C : 0.21%	0.47%																										
900°C : 0.72%	3.59%																										
1000°C: 2.00%	3.60%																										
Linear	Thickness																										
300°C : 0.02%	0.08%																										
500°C : 0.07%	0.18%																										
750°C : 0.13%	0.42%																										
900°C : 0.64%	1.03%																										
1000°C: 1.64%	4.00%																										

RESULTS AND DISCUSSION

Table 2 shows the measured re-ignition times of various samples at heat flux levels between 40 and 60 kW/m² as a function of the water application time. It can be seen from Table 2 that for each sample, as the heat flux was decreased, the re-ignition time was increased. On the other hand the re-ignition time was increased as a result of the increase in the water application time.

Figure 2 shows a typical temperature history profile for surrogate samples. This particular graph corresponds to a sample with 72.9% porosity and 25 mm thickness. The drop in the temperature is essentially due to the cooling effect of the water droplets. As can be seen, this drop is followed by an increase in the temperature due to the continuation of the heating process. The re-ignition time generally correlates with the distance of the thermocouple from the top surface.

As Figure 2 indicates, at the top surface the water application has a strong influence on the temperature change, which is initially at around 480°C and sharply drops down to 80°C after the application of the water spray. Meanwhile, at the bottom surface the influence of water application is relatively weak, primarily because the cooling wave has not penetrated deep enough into the sample.

The effect of different water application times on the top surface temperature profile is shown in Figure 3 for a sample with 53.5% porosity and 25 mm thickness. Similar behaviour was observed for other samples. As Figure 3 shows, in general, the trends of curves for different water application times are similar. The only difference is the re-ignition time (the time at which the temperature reaches its value prior to cooling). The higher the water application time, the longer is the recovery time period and, therefore, the longer the re-ignition time.

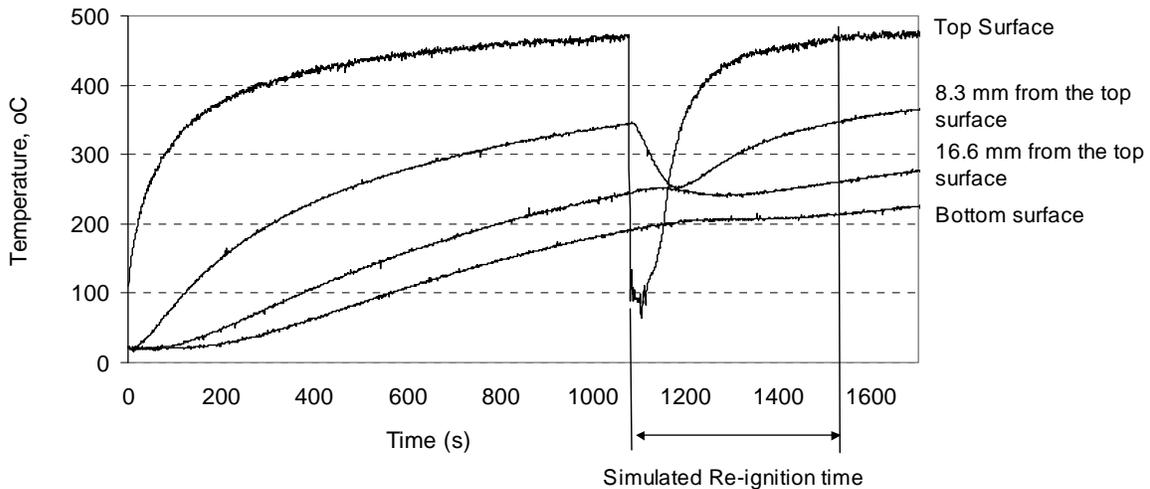


Figure 2: Temperature profiles within a 25 mm thick ceramic sample with a porosity of 72.9% exposed to a heat flux level of 40 kW/m².

Table 2: Summary of measured re-ignition times.

Sample	Water application Time (s)	Re-Ignition time (s)		
		60 kW/m ²	50 kW/m ²	40 kW/m ²
Isomag 45, 2.5 cm	5	312	348	403
	10	342	382	443
	15	396	450	501
Isomag 70, 2.5 cm	5	264	301	342
	10	318	360	405
	15	371	425	474
Isomag 45, 1.2 cm	5	507	548	567
	10	579	595	627
	15	663	696	
Isomag 70, 1.2 cm	5	465	514	538
	10	541	572	602
	15	625	671	
Isomag 110, 1.2 cm	5	404	448	487
	10	503	540	576
	15	598	644	

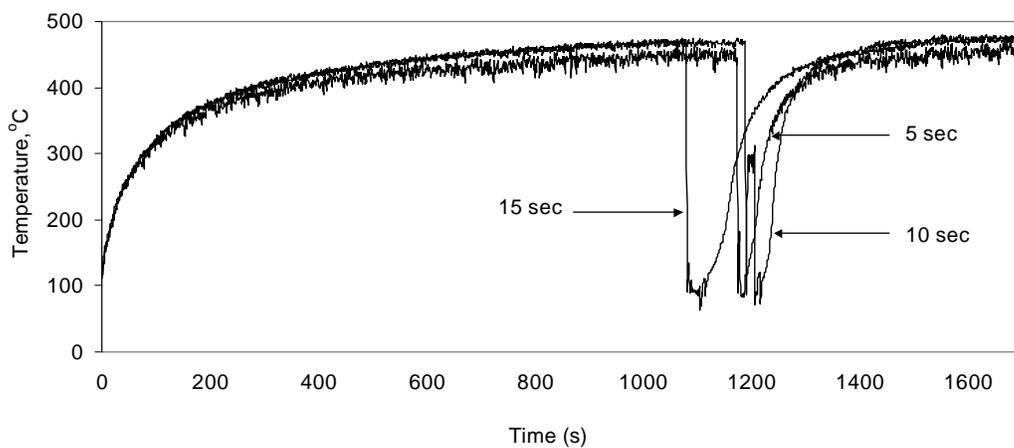


Figure 3: Surface temperature versus time for a 25 mm thick sample with a porosity of 53.5% exposed to a heat flux level of 40 kW/m².

As Figure 4 illustrates, the mass of the sample increases as a result of water applied, and after water droplets have completely evaporated the mass of the sample returns to its initial value since there is no mass loss due to chemical/thermal reactions. Therefore, the overall re-ignition time increases as the water application time is increased simply because there is more water to be evaporated (Figure 4). The results indicate that the average water evaporation rate is a function of the external heat flux and sample thickness. The average evaporation rate for thick samples varied between 0.0103 g/s (for 5 s application time) and 0.0153 g/s (for the 15 s application time).

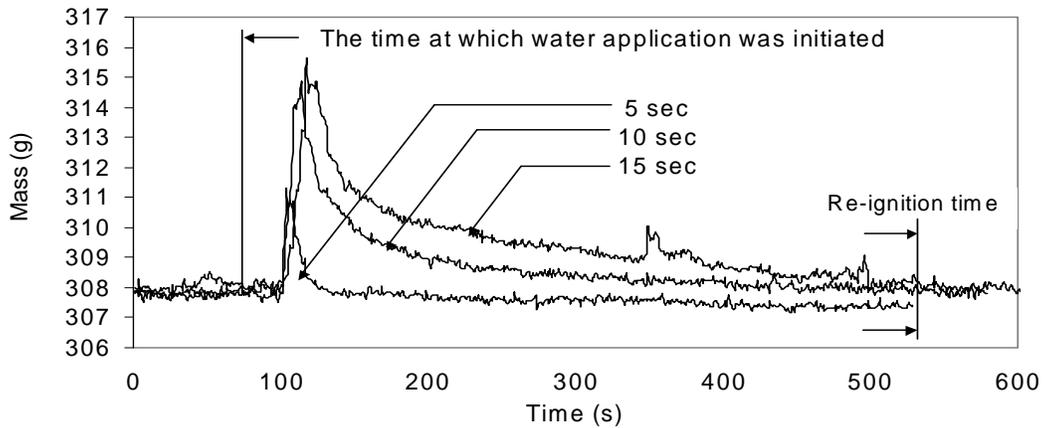


Figure 4: Mass loss of water versus time for a 25 mm thick sample with a porosity level of 53.5% exposed to a heat flux level of 50 kW/m².

The re-ignition times on the top surface of the surrogate samples are shown in Figures 5 and 6 as a function of heat flux level and material porosity. While Figure 5 illustrates the results for 25 mm thick samples, Figure 6 shows those that correspond to 12 mm samples.

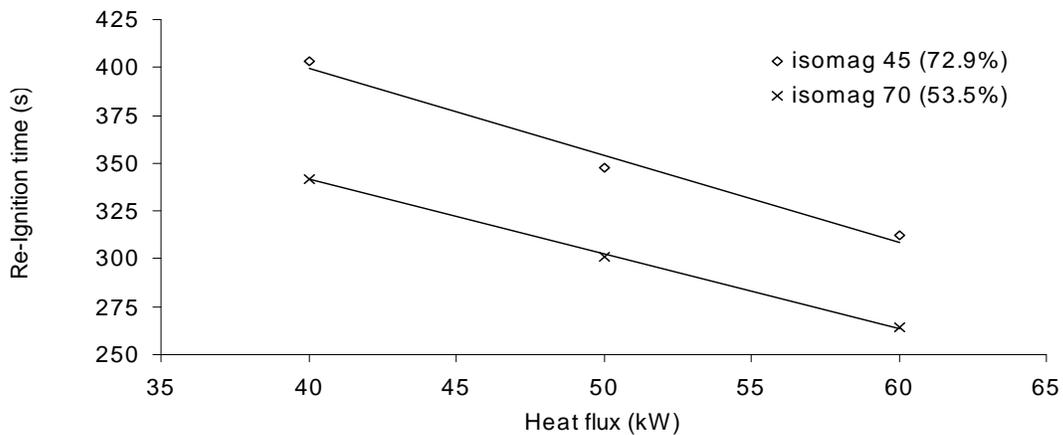


Figure 5: Re-ignition time versus heat flux of a 12 mm thick sample.

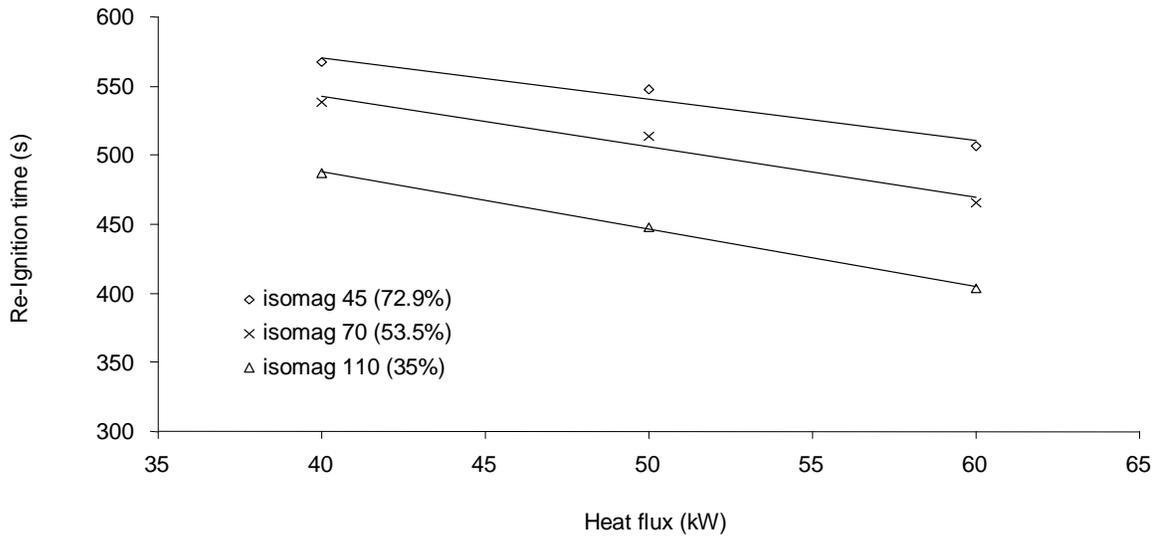


Figure 6. Re-ignition time versus heat flux of a 12 mm thick sample.

As shown in Figures 5 and 6, for all porosity levels the re-ignition time decreases linearly with the increase of the heat flux. This is simply because more thermal energy is available for evaporation of water droplets when samples are exposed to high heat flux levels.

Figures 5 and 6 also show that at a given heat flux level, the re-ignition times of samples having higher 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, 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.

The influence of the amount of water on the re-ignition times for samples with different porosities is shown in Figure 7. As illustrated, the re-ignition time increases with the increase of water application simply because the cooling effect is more pronounced. As shown in Figure 7, regardless of the porosity level, all samples exhibit very similar re-ignition times at higher water application times (e.g. 15 s). This can be assigned to the fact that after a certain time period when the pores within the sample are saturated with water, the water droplets start to run-off from the edges of the sample. Thus, despite their porosity level, samples effectively absorb the same amount of water and, hence, behave similarly.

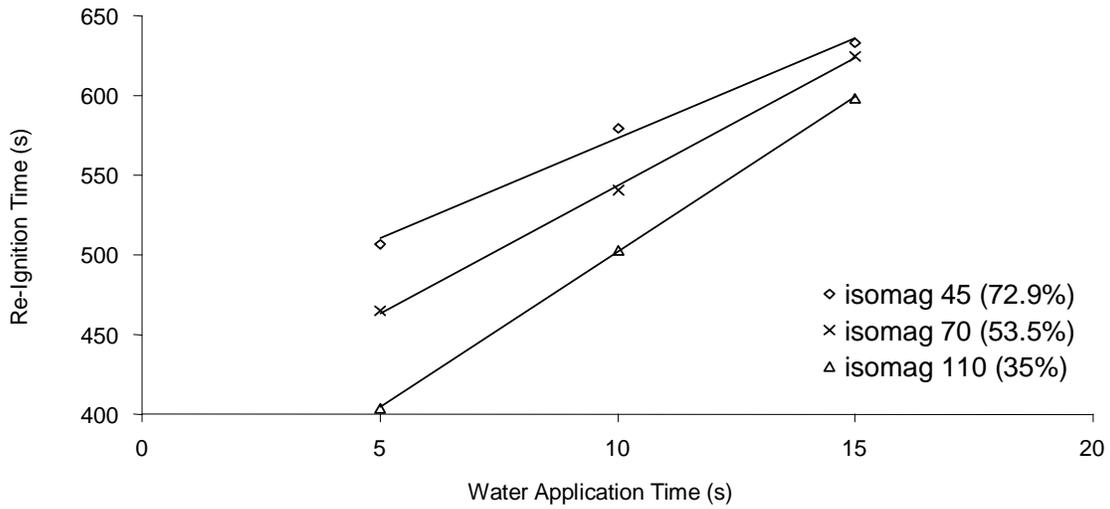


Figure 7. Re-ignition time versus water application time for 12 mm thick samples at a heat flux level of 60 kW/m².

The relationship between heat flux and re-ignition time of samples with different thicknesses is shown in Figure 8. As illustrated, the re-ignition time of a thin sample is higher than the re-ignition time of a thick one. This phenomenon is not fully understood. Although it could be a consequence of having two different temperature levels for thin (600⁰C) and thick (480⁰C) samples. The authors are currently investigating this issue and will report the result in a future publication.

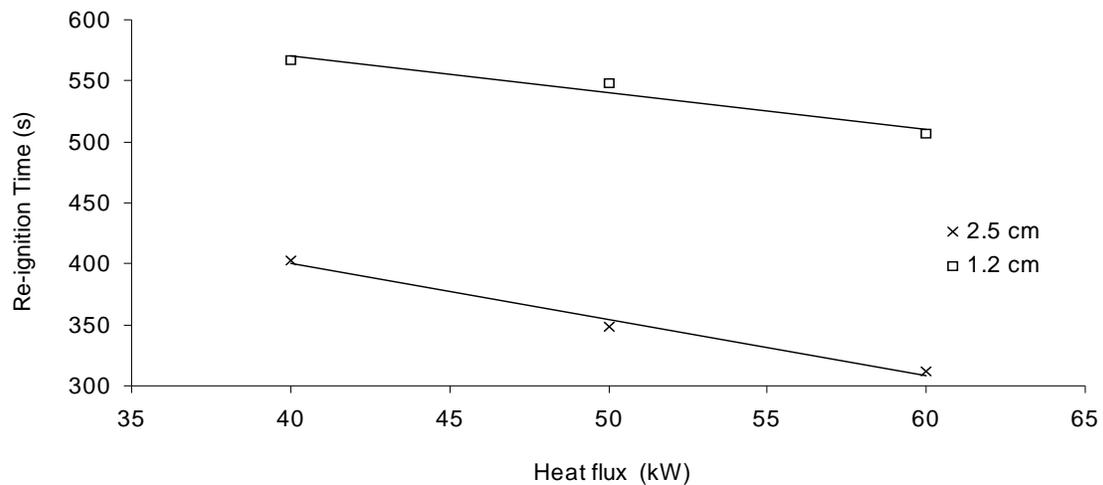


Figure 8: Re-ignition time versus heat flux of isomag 45 (72.9%).

CONCLUSIONS

This study leads to the following conclusions regarding the impact of material porosity on the re-ignition phenomenon:

1. The re-ignition time is strongly affected by the material porosity.
2. The re-ignition time decreases linearly with the increase of the external heat flux and increases with the increase of sample porosity.
3. The re-ignition time is inversely proportional to the material thickness.

REFERENCES

1. Depew, C.A., Corlett, R.C., Yu, T.I., and Gruz, G.A., "Response of Wood Boards to Radiative Heating and Water Spray", Fall Meeting of the Western State Section of the Combustion Institute, El Segundo, CA, USA, 1973.
2. Usui, K., Transaction of the Architectural Institute of Japan, 41, 100, 1950.
3. Takahashi, S., "On the Re-ignition"., Bulletin of Japanese Association of Fire Science Engineering, 32, 41-42, 1982.
4. Takahashi, S., A Theoretical Study on the Requirements of Water Application for a Compartment Fire Extinction", Bulletin of Japanese Association of Fire Science and Engineering, 34, 1984.
5. Takahashi, S., "Re-ignition of the Carbonised Wood and the Water Soaked Wood Ember", report of Fire Research Institute of Japan, 58, 1984.
6. Takahashi, S., "Experiments and Theory in the Extinction of a Wood Crib", Fire Safety Science-Proceedings of the First International Symposium, 1197-1206, 1986.
7. Rawet, D., Smith, R., and Kravainis, G., "A Comparison of Water Additives for Mopping-up After Forrest Fires", Int. J. Wildland Fire 6(1): 37-43, 1996.
8. Moghtaderi, B., Novozhilov, V., Kent, J.H., Fletcher, D.H., and Apte, V.B., "Effects of Water Spray on Re-ignition Characteristics of Solid Fuels", Fire Safety Science-Proceedings of the Fifth International Symposium, 829-840, 1997.
9. Moghtaderi, B., Dlugogorski, B.Z., Kennedy, E.M., and Fletcher, D.F., "Effects of the Structural Properties of Solid Fuels on Their Re-ignition Characteristics", Fire and Materials, 22, 155-165, 1998.