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Influence of moisture on autoignition of woods in cone calorimeter

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Abstract

Six species of wood samples, namely, pine, beech, cherry, oak, maple, and ash, were investigated by autoignition in a cone calorimeter to identify the influence of moisture on autoignition. It was observed that (1) for autoignition, as different from piloted ignition, there is no obvious trend in ignition temperature when moisture content increases from 0% to 11%; (2) ignition temperature decreases with a higher external heat flux, and the influence of specimen thickness to the ignition temperature can be ignored; (3) ignition time correlates linearly with $\rho^{0.73}/(\dot{q}'' - 28.0)^{1.82}$, and the coefficient rises with the increase of moisture content; and (4) the influence of moisture to the average mass loss rate and time at 50% mass loss can be ignored if the moisture content of wood sample is lower than 11%.

Keywords

Wood, moisture content, autoignition, ignition temperature, ignition time, mass loss rate

Introduction

Ignition tends to mean two different things[1]: (1) kindled ignition where a body is ignited by an external heat source, such as flame, sparks, or hot surface, and in general, the measurement of ignition point based on the American Society for Testing and Materials (ASTM) is widely used; and (2) autoignition (or self-ignition, spontaneous ignition, nonflaming ignition) where certain combustible materials can ignite as a result of internal heating, which arises spontaneously if there is an exothermic process liberating heat faster than it can be lost to the surrounding. Most of the previous studies focused only on the kindled ignition of

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Table 1. Measured properties of wood samples

Species	Material	Grain orientation	Dry wood	Wet wood	
			Average density (kg/m^3)	Average density (kg/m^3)	Average moisture content (%)
Softwood	Pine	Along	392.7	446.8	12.1
Hardwood	Beech	Along	566.6	632.4	10.4
	Cherry	Along	494.6	557.6	11.3
	Oak	Along	804.0	897.3	10.4
	Maple	Along	673.4	748.2	10.0
	Ash	Along	610.6	680.0	10.2

woods.[2–7] Although the kindled ignition is very common, it is not instrumented to account for flow effects, in-depth radiation effects, and ambiguities resulting from the emission spectral characteristics of the material and the heat flux source.[8]

Much work has been done focusing on the influence of moisture to ignition properties of wood samples by kindled ignition. Atreya and Abu-Zaid[9] showed that ignition time increases with a lower external heat flux or a higher moisture content. Experiments conducted by Moghtaderi et al.[10] revealed that the effect of moisture content on the piloted ignition process is significant, and the ignition temperature is significantly affected by both moisture content and external heat flux. Simms and Law[11] studied the effect of varying the moisture content on both the piloted and autoignition of wood samples. The results showed that the effect of moisture for any given wood is to increase the ignition time, the total ignition energy, and the minimum intensity for both pilot ignition and autoignition.

Six species of wood samples were investigated experimentally by autoignition in a cone calorimeter. The objectives of this study are as follows:

- To identify the influence of moisture to the ignition temperature and ignition time by autoignition when wood samples are under external heat flux
- To analyze the influence of moisture to the average mass loss and time at 50% mass loss by autoignition
- To provide input parameters or validation data for numerical models of woods under external heat flux by autoignition

Methodology

Materials

Measured properties of wood samples are listed in Table 1. The sample sizes are 100 mm × 100 mm with different thicknesses, such as 10, 20, and 30 mm.

Both dry and wet wood specimens were conditioned under the same relative humidity for more than 24 h. For dry wood, the specimens were conditioned in a furnace at a range of 102–105°C. Moisture contents (wet basis) were measured according to the ovendry method.[12] Periodical weighing was performed until no further weight loss was registered. Specimens with three different thicknesses were prepared.

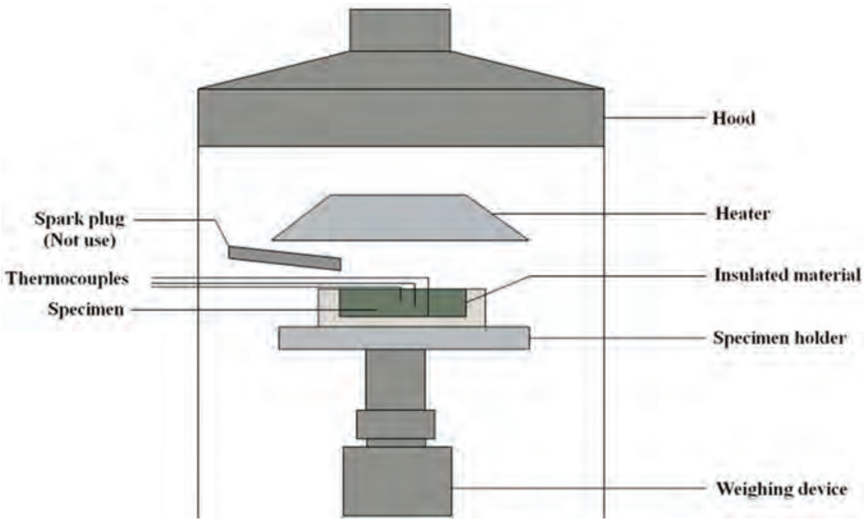

Figure 1. The view of wood sample in cone calorimeter.

Apparatus

Cone calorimeter as a frequent equipment for piloted or autoignition experiments was used in this study.[13] Wood samples were put in horizontal orientation on specimen holder. External heat fluxes of 25, 50, and 75 kW/m^2 were chosen for this study. Thermocouples were used to measure the temperatures at wood surface and different depths, as shown in Figure 1.

Procedure

Before experiments, gas analyzers and external heat flux were first calibrated accordingly. The wood samples were then secured on a specimen holder and placed under the heater. The edges and rear surface of the specimens were covered with aluminum foil for insulation. Change in weight was dynamically recorded using the built-in weighting device. The temperatures at surface and different depths of wood samples were recorded using a data logger. A sample was considered ignited when flame was first observed. The surface temperature measured at ignition was considered as ignition temperature. The experiments ended when flame was out. Spark plug was not used during the whole experiments.

Result and discussion

Ignition temperature

Table 2 shows the ignition time and ignition temperature of dry wood and wet wood samples. It is known that the range of ignition time of dry wood is 7–49 s, and wet wood is 10–119 s. The ignition time largely increases with higher moisture content. The range of ignition temperature for dry wood is about 267–525°C and for wet wood is about 264–558°C. The moisture content may have little influence to the ignition temperature. Atreya and Abu-Zaid[9] analyzed the effect of environmental variables on piloted ignition of woods. It was

Table 2. Ignition time and ignition temperature of dry wood and wet wood samples

Material	Thickness (mm)	Dry woods				Woods with about 11% moisture content			
		50-kW/m^2 heat flux		75-kW/m^2 heat flux		50-kW/m^2 heat flux		75-kW/m^2 heat flux	
		Ignition time (s)	Ignition temperature (°C)	Ignition time (s)	Ignition temperature (°C)	Ignition time (s)	Ignition temperature (°C)	Ignition time (s)	Ignition temperature (°C)
Pine	10	23	397.9	9	374.9	61	558.2	23	348.6
	20	33	478.5	7	313.4	48	433.8	11	306.6
	30	21	387.7	9	344.9	27	433.1	12	314.0
Beech	10	30	441.1	11	267.2	46	370.6	20	338.0
	20	23	359.5	12	325.9	45	503.8	13	270.4
	30	22	420.1	9	340.4	39	370.6	18	378.9
Cherry	10	28	416.5	9	288.6	54	465.4	16	425.0
	20	27	402.5	9	371.2	57	543.6	11	334.4
	27	40	525.6	7	310.6	37	433.1	10	346.5
Oak	10	42	443.7	15	322.2	119	511.7	26	482.2
	20	36	406.3	14	406.3	79	453.5	24	353.7
	30	49	455.8	10	312.7	57	488.6	23	398.6
Maple	10	37	439.9	14	315.0	87	436.0	27	332.4
	20	47	465.2	13	347.7	87	491.1	26	399.2
	30	35	418.5	10	409.8	56	393.0	18	361.1
Ash	10	24	422.0	12	281.6	59	425.6	21	291.7
	20	N/A	N/A	13	350.1	57	487.6	19	340.9
	30	29	438.8	8	358.5	23	346	13	264.4

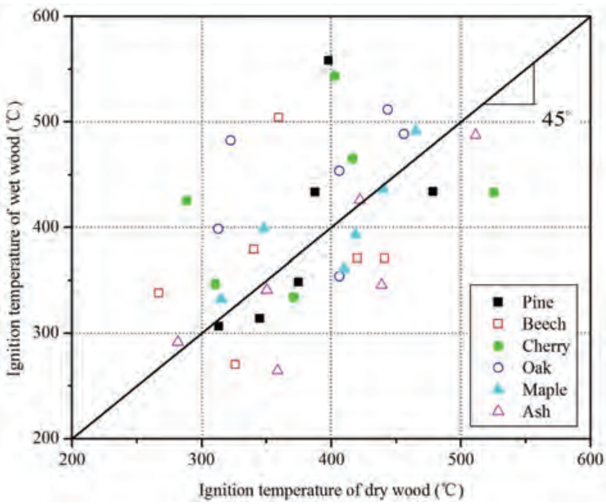

Figure 2. Comparison of ignition temperature between dry wood and wet wood.

found that the surface temperature at ignition is higher for higher moisture content. This may indicate that the ignition temperature of autoignition is different from that of piloted ignition.

Figure 2 shows the comparison of ignition temperature between dry wood and wet wood. No obvious trend was observed for moisture content between 0% and 11%. Similar results were observed by Moqbel et al.[14]

The Pearson's correlation coefficient was adopted to examine the influence of moisture content to the ignition temperature

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \cdot \sum (y_i - \bar{y})^2}} \tag{1}$$

Correlation coefficient between ignition temperature and moisture content was obtained as 0.12, indicating that the effect of moisture content is insignificant.

Equation (1) is used to examine the correlation coefficient between ignition temperature and external heat flux. The correlation coefficient is obtained as −0.7169, which indicates that the ignition temperature decreases with a higher external heat flux. Figure 3 shows the influence of external heat flux to ignition temperature. It is observed that almost all the data are positioned in the lower half of the plot, which means that the ignition temperature decreases when the external heat flux is increasing. Experiments under 25 kW/m^2 of external heat flux were also conducted, with no flame observed during whole experimental time. This means that the critical heat flux of wood by flaming autoignition is higher than 25 kW/m^2. Mehaffey[15] obtained that critical heat flux of woods is about 28 kW/m^2. For glowing or smoldering ignition, experiments[16–18] showed that its critical heat flux is possible down to a flux level of 7.5 kW/m^2.

The correlation coefficient between ignition temperature and specimen thickness is obtained as −0.04, which means the influence of specimen thickness to ignition temperature can be ignored.

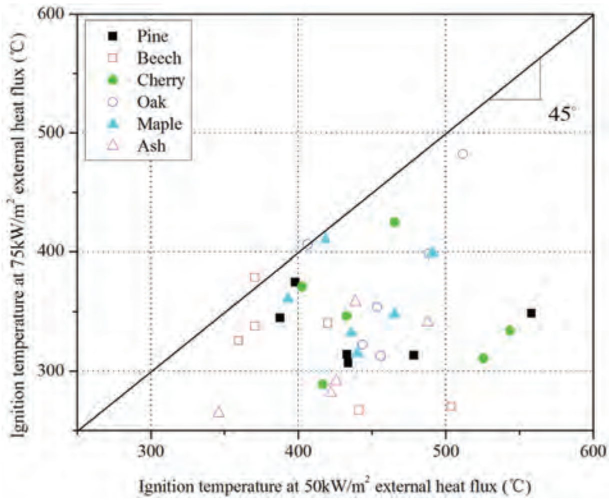

Figure 3. The influence of external heat flux to ignition temperature.

Ignition time

Figure 4 shows a comparison of ignition time between dry wood and wet wood samples. It is noticed that almost all the points are located in the upper half of the figure, indicating that the ignition time is largely dependent on moisture content. It is observed that ignition time increases with higher moisture content. However, the correlation between ignition time of wet wood and dry wood is difficult to be identified from Figure 4 because thermal properties of these two are different.

Babrauskas[19] has obtained a correlation of ignition time by experimental data on cone calorimeter, which is given as

$$t_{ig} = \frac{130\rho^{0.73}}{(\dot{q}'' - 11.0)^{1.82}} \tag{2}$$

where t_{ig} is the ignition time of wood samples, s; ρ is the density, kg/m^3; and $\dot{q}''$ is the external heat flux, kW/m^2. In this equation, if $\dot{q}'' \to 11.0$, then $t_{ig} \to \infty$. This means that the critical heat flux of wood by piloted ignition is about 11 kW/m^2.

Mehaffey[15] showed that critical heat flux of wood by flaming autoignition is about 28 kW/m^2. Therefore, for autoignition, if $\dot{q}'' \to 28.0$, then $t_{ig} \to \infty$. Based on this, a correlation is assumed as

$$t_{ig} = a \cdot \frac{\rho^{0.73}}{(\dot{q}'' - 28.0)^{1.82}} \tag{3}$$

Figure 5 shows a correlation between ignition time of dry wood samples and other factors by using equation (3). The ignition time of dry wood samples correlated linearly with $\rho^{0.73}/(\dot{q}'' - 28.0)^{1.82}$, which can be given as

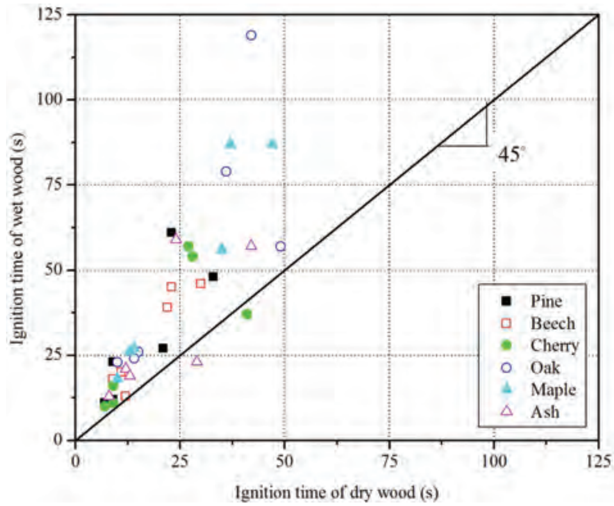

Figure 4. Comparison of ignition time between dry wood and wet wood samples.

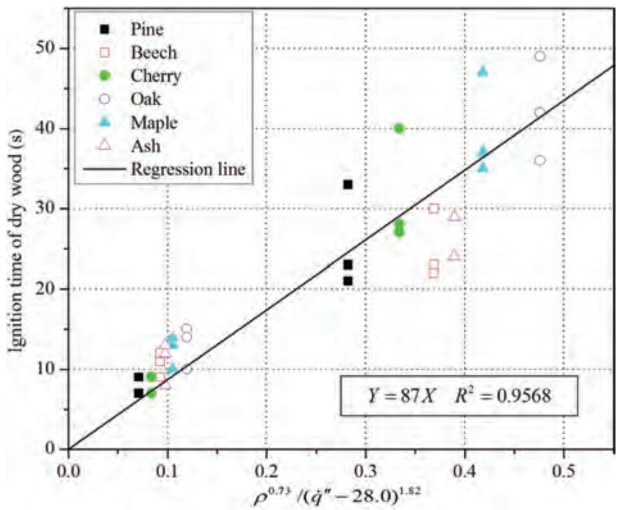

Figure 5. Correlation between ignition time of dry wood and other factors.

$$t_{ig,\,dry} = \frac{87\rho^{0.73}}{(\dot{q}'' - 28.0)^{1.82}} \tag{4}$$

where $t_{ig,\,dry}$ is the ignition time of dry wood samples, s.

Figure 6 shows a correlation between ignition time of wet wood samples and other factors by using equation (3). The ignition time of wet wood samples also correlated linearly with $\rho^{0.73}/(\dot{q}'' - 28.0)^{1.82}$, which can be given by

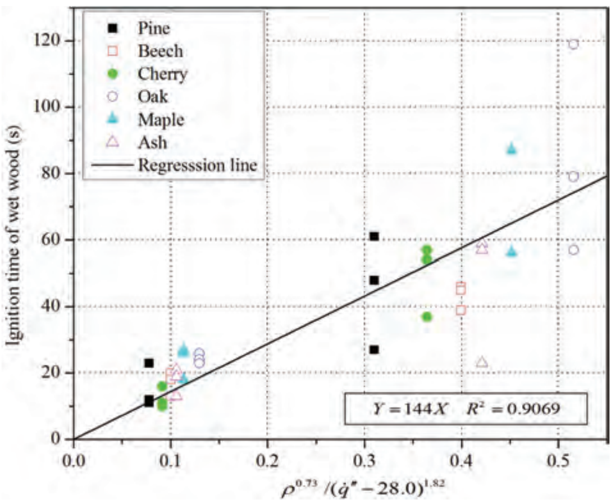

Figure 6. Correlation between ignition time of wet wood and other factors.

$$t_{ig,wet} = \frac{144\rho^{0.73}}{(\dot{q}'' - 28.0)^{1.82}} \tag{5}$$

where $t_{ig,wet}$ is the ignition time of wet wood samples, s.

From equations (4) and (5), it is noticed that the coefficients of these two equations are different. The ignition time is largely affected by moisture content. So it might be shown that the coefficients in these two equations are dependent on the moisture content. A simple linear regression between ignition time and moisture content was found to be the best fit for all the forest species tested by Dimitrakopoulos et al.[20] The ignition time of wood samples dependent on moisture content can be obtained as

$$t_{ig} = (87 + 518\omega)\frac{\rho^{0.73}}{(\dot{q}'' - 28.0)^{1.82}} \tag{6}$$

where t_{ig} is the ignition time for both dry wood and wet wood samples, s; and ω is the moisture content of wood sample, 0–0.3.

Figure 7 shows the comparison between predicted ignition time using equation (6) and experimental data. It is observed that these two kinds of values correlate well.

Mass loss rate

During the experiments, thermocouples were used to measure temperature at different depths of the wood slab. Holes were drilled to insert these thermocouple wires. Under the influence of these thermocouple wires, some noises were observed in the mass loss history data. Savitzky–Golay method[21] was used to solve this problem.

Figure 8 shows the comparison of average mass loss rate between dry wood and wet wood. Comprehensively, no big difference is observed between the average mass loss rate of

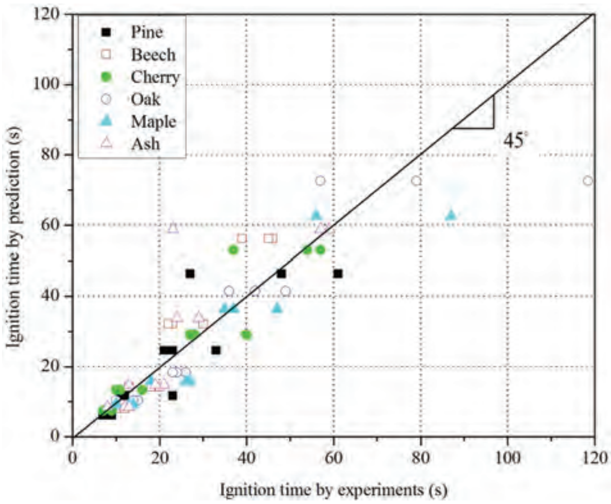

Figure 7. Comparison of ignition time between prediction and experiments.

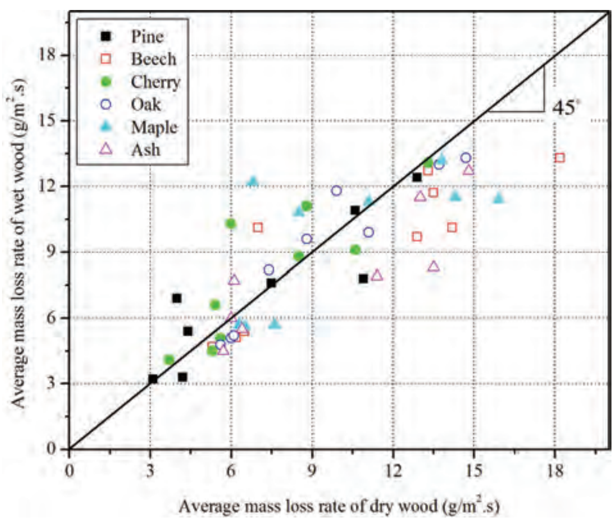

Figure 8. Comparison of average mass loss rate between dry wood and wet wood.

dry wood and wet wood. The correlation between dry wood and wet wood is difficult to be identified accurately from Figure 8 because of the difference of density.

A correlation between average mass loss rate and influencing factors were obtained from a previous study,[22] which was given as

$$MLR_{ave} = 0.016L^{0.2}\dot{q}''^{0.8}\rho^{0.4} \tag{7}$$

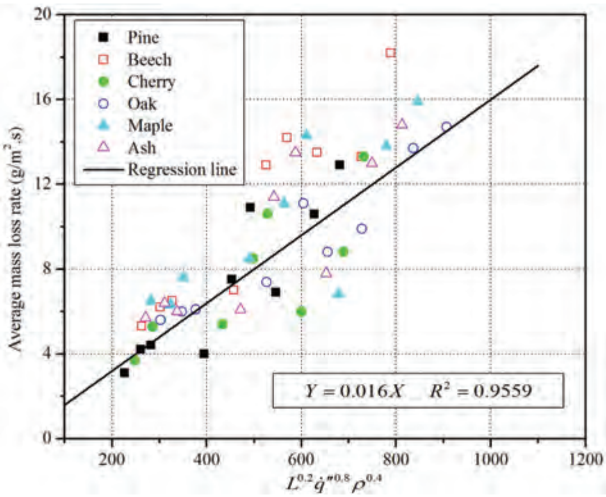

Figure 9. Correlation between average mass loss rate of dry wood and other factors.

where MLR_{ave} is the average mass loss rate between experiment start and 50% mass loss, $g/m^2 \cdot s$; and L is the thickness of wood samples, mm.

Figure 9 shows a correlation between average mass loss rate of dry wood and other factors using equation (7). It is noticed that these two correlates linearly well. It is also noticed from Figure 9 that same coefficient is obtained for both dry wood and wet wood. This might indicate that the influence of moisture content to the average mass loss rate can be ignored.

Equation (1) is used to examine the influence of moisture content to average mass loss rate. The result shows that the correlation coefficient between average mass loss rate and moisture content is low as −0.08, indicating that the moisture content of woods can be ignored. Similar results were observed by Lee and Diehl.[23] The results suggested that difference in mass loss rate between dry and wet woods is mainly the water, and the absorbed water does not seem to affect the basic wood pyrolysis process. Saito et al.[24] analyzed the effect of water content on combustion characteristics and provided that the ignition started before the water was removed completely. In this study, the average mass loss rate was considered in a long period, and water inside the wood slab was removed completely after ignition. Therefore, the absorbed water then seems to have little influence to the average mass loss rate.

The time at 50% mass loss also can be obtained by original mass loss and average mass loss rate, which can be given as

$$t_{50} = 32.5 \frac{L^{0.8} \rho^{0.6}}{\dot{q}''^{0.8}} \; (0 \leq \omega \leq 0.11) \tag{8}$$

where t_{50} is the time at 50% mass loss, s.

Figure 10 shows a comparison of time at 50% mass loss between experimental data and prediction. It is noticed that the prediction is with great accuracy when the time is less than 800 s, and the predicted time is a little higher when time is longer than 800 s. External heat flux used in experiments is low when the time at 50% mass loss is more than 800 s. The time

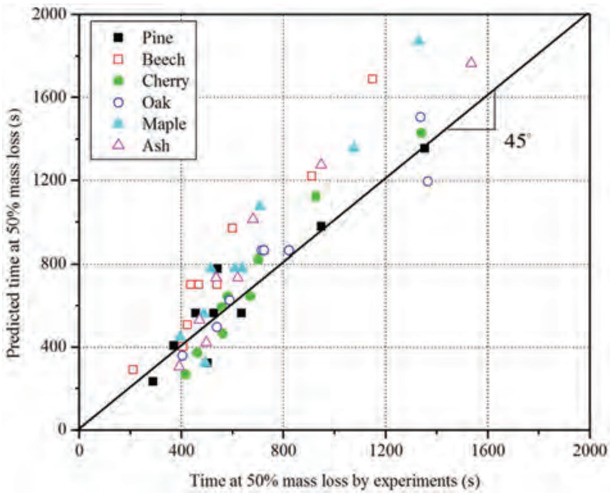

Figure 10. Comparison of time at 50% mass loss between experimental data and prediction.

of evaporation may be slightly affected under low external heat flux, which may delay the time of 50% mass loss.

Conclusion

Six species of wood samples, namely pine, beech, cherry, oak, maple, and ash, were investigated to identify the influence of moisture on autoignition. The following conclusions can be addressed:

1. For piloted ignition, previous studies showed that the surface temperature at ignition is higher with higher moisture content. Differently, no obvious trend was observed for autoignition when moisture content increases from 0% to 11%. Ignition temperature decreases with a higher external heat flux, and the influence of specimen thickness to the ignition temperature can be ignored.
2. Ignition time by autoignition increases with higher moisture content. The influence of moisture is on the coefficient of the correlation. Ignition time of wood samples dependent on moisture content is obtained as

$$t_{ig} = (87 + 518\omega)\frac{\rho^{0.73}}{(\dot{q}'' - 28.0)^{1.82}}$$

3. The influence of moisture to the average mass loss rate can be ignored when moisture content is lower than 11%. The average mass loss rate is

$$MLR_{ave} = 0.016L^{0.2}\dot{q}''^{0.8}\rho^{0.4}(0 \leqslant \omega \leqslant 0.11)$$

4. Similarly, the influence of moisture content to the time at 50% can be ignored. The correlation is given as

$$t_{50} = 32.5 \frac{L^{0.8} \rho^{0.6}}{\dot{q}''^{0.8}} \quad (0 \leqslant \omega \leqslant 0.11)$$

These empirical equations and data in this study not only can be used to predict ignition time, average mass loss rate of woods under external heat flux by autoignition, but also could provide input parameters for numerical modeling or be used for modeling validation.

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