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Studies of ignition behaviour of biomass particles in a down-fire reactor for improving co-firing performance

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Abstract

To realize large percentage biomass co-firing with coal in existing coal-fired boilers, the combustion behaviour of biomass is expected to be similar or comparable to that of coal. When co-firing with coal, biomass is not necessarily to be ground as fine as the dedicated coal particles due to its higher reactivity. With aim of achieving promising performance of co-firing with dedicated coal particles, the determination of suitable particle size of biomass becomes important. The paper investigates experimentally the ignition behaviour of three biomass materials in a down-fire reactor associated with thermogravimetric analyser (TGA). TGA results showed that the devolatilization process is accelerated by the presence of oxygen, but failed to identify the impacts of particle size on the ignition behaviour of biomass. However, the ignition testing results based in the down-fire reactor clearly showed that ignition delay time of a large biomass particle is longer than that of smaller one. In addition, being injected into the furnace, the softwood particles take a longer residence time to be ignited than the straw particles at same sizes, which agrees well with their reactivity analysis in TGA. Moreover, the ignition test results suggested that the ignition mechanism of biomass could be alternated from homogeneous to the heterogeneous ignition when the furnace temperature is increasing; at high enough furnace temperatures, the ignition predictably occurs at the particle surface without requiring the start of devolatilization. The results quantitatively demonstrate the effects of particle size on the ignition delay time of biomass, which, together with the transport phenomena and surrounding atmosphere, can contribute to control the biomass combustion profile and co-firing performance.

Keywords: Biomass, ignition delay time, Co-firing, down-fire reactor

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1 Introduction

Biomass can be used as sustainable fuel across the energy spectrum for electricity, heat and transport. Compared to other thermal utilizations, biomass co-firing has been identified as a near term, low cost, and transitional means to increase biomass power capacity and reduce carbon emission. It has been demonstrated that biomass can potentially substitute more than 50% of the coal in a co-firing configuration, but at present the actual co-firing levels in most commercial applications are only 5-10% on thermal basis[1]. When co-firing biomass with coal in existing coal-fired boilers, the differences of fuel properties between biomass and coal complicate the processes of fuel mixture handling and combustion. Typically, the high moisture content inherent in biomass requires more energy for drying and milling, resulting in decreased overall energy efficiency and increasing difficulties in fuel handling and processing; while high oxygen and volatile contents of biomass might cause the discrepancies in combustion process when co-combustion with coal. Those technical challenges become critical when increasing the biomass co-firing ratios, and thus limit the widespread utilizations of biomass in power generation sectors.

Ignition is considered as the process initiating the combustion and recognized as a critical step due to its impacts on the lift-off distance, flame profile and stability, and pollutants formation, with consequent influence on the boiler operation, energy efficiency, and emissions. Accordingly, understanding of the ignition behaviour of biomass is essential in optimization of the biomass combustion or co-firing process. It is known that ignition of solid fuel is the result of a complex interaction among different mechanisms including particle heating, devolatilization, heterogeneous oxidation, and gas-phase oxidation and transport phenomena[2]. As regards to the reported ignition mechanisms, coal ignites either homogeneously as ignition of volatile matter evolved into the surrounding gas phase by pyrolysis of the coal particle, or heterogeneously as oxygen directly attacks the surface of the particle[3]. However, according to most ignition studies of coal particles, factors bringing about a given mechanism are still in disagreement since it is a challenge to identify it via experimental approaches. Based on the theoretical definition of ignition type proposed by Zhang and Wall[2], high volatile content in coal normally leads to a homogeneous ignition.

Compared to coal, biomass contains high volatiles and is known having a lower ignition temperature. The ignition or explosion of biomass dust clouds is of interest in the fields of fire safety, which gained intensive research interests and has raised concerns over its safe handling and utilization[4, 5]. Grotkjær et al. [4] conducted pulse ignition and thermogravimetric studies to determine the ignition temperature of three biomass materials. The results showed that the ignition process is initiated by oxidation reactions on the biomass particle surface, and then the

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3 volatiles form a homogeneous diffusion flame away from the particle surface. Jones et al. [5]
4 recently observed that ignition took place on the very reactive char particle formed via pyrolysis
5 while flaming combustion of volatiles was not observed, and thus concluded that biomass
6 ignition as heterogeneous but the results are based on smoldering combustion. With respect to
7 biomass and coal co-firing, Riaza et al. [6] experimentally observed that the ignition behavior of
8 the coals is improved by adding biomass in either air or oxy-firing conditions, particularly
9 noticeable in the ignition of the high rank coal. Similarly, Toptas et al. [7] found that a blend of
10 torrefied biomass with lignite coal has a reduced ignition temperature than lignite itself, and this
11 was explained as the modified reactivity was a consequence of torrefaction of biomass but no
12 interaction of lignite-biomass was seen in the first stage of co-combustion.
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20 The characterization of solid fuel ignition is complicated since the ignition temperature is not a
21 fundamental parameter of the fuel, which highly depends on the particle size, heating rate of the
22 particle, and the surrounding gas[4]. When a fine biomass particle enters a pulverized fuel flame,
23 it is rapidly heated to a final temperature that is far above its ignition temperature. Therefore, in
24 the real combustion process, the ignition delay time becomes a key parameter, which together
25 with transport phenomena determines the lift-off distance of flame and consequent the flame
26 profile. To achieve large percentage biomass co-firing in existing coal-fired boilers, the ignition
27 and the consequent combustion properties of biomass are expected to be similar or comparable
28 to that of coal.
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35 Particle size distribution is essentially controlled for efficiently processing coal particles in
36 dedicated coal-fired boilers. When co-firing biomass in these coal-fired boilers, it is believed that
37 biomass does not need to be ground as fine as dedicated coal particles, because the reactivity of
38 biomass is higher than that of coal, and thus biomass particles could be burnt out quickly inside
39 boilers even at bigger sizes [8]. Moreover, fine biomass particles are not favored with respect to
40 energy saving and co-firing performance. Cutting down the biomass sizes requires intensive
41 energy due to the fiber structure and high moisture content of biomass. In addition, fine biomass
42 particles can be ignited immediately, which is unwanted process as the major heat of its
43 combustion is released at an early stage. Consequently, the high temperature flame will primarily
44 occur near the burner ports, leading to an extremely uneven heat distribution inside the furnace
45 and thus unstable parameters of steam. However, an overlarge particle size of biomass should
46 also be avoided because its ignition could be delayed, and thus a considerable amount of un-
47 burnt carbon might still remain in fly ash losing the thermal conversion efficiency. Therefore,
48 understanding the influences of biomass particle size on ignition delay time is essential to
49 determine the preferable sizes of biomass particles. This allows to achieve an expected co-firing
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3 flame profile without boiler retrofitting and also ensure complete combustion of biomass
4 particles before leaving furnace exit, as well as to cut the energy consumption in milling systems.
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7 However, the effects of particle size on biomass ignition delay time and consequent combustion
8 process are still unclear, which limits the control of a preferable flame profile and consequent
9 combustion process. The impacts of particle sizes on coal ignition have been previously studied
10 experimentally on coal dust stream [9] or numerically on a single particle[10]. Obviously, due to
11 the significantly different fuel properties of coal and biomass, coal ignition behavior couldn't be
12 referenced for the understanding of biomass ignition properties. Regarding to the coal and
13 biomass fuel mixture, Trabadela [11] tested particle size effects on the coal and biomass ignition,
14 and their results showed that the ignitions of fine biomass particles behaved similar in either air
15 or oxygen enriched conditions, while larger particles of biomass did not ignite even under
16 oxygen enriched atmosphere; however, only two different sizes of biomass particles were
17 analyzed, which are insufficient to demonstrate a reasonable trend. In this work, straw, softwood
18 and torrefied softwood have been initially analyzed in TGA to understand their thermal
19 performances at varying conditions; the TGA results are then used as the supportive
20 fundamentals for understanding the tested ignition behavior of the biomass in a down-fire
21 reactor. In addition, the ignition delay time of three types of biomass at varying particles sizes
22 and furnace temperatures are determined by detecting the luminance changes inside the reactor
23 before and after biomass ignition using the photosensitive elements that are equipped in the top
24 of reactor. Finally, the timescales of ignition and devolatilization at varying degrees have been
25 compared and comprehensively discussed.
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38 **2 Methodologies**

39 **2.1 Down-fire reactor**

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42 The ignition behavior of biomass particles is investigated experimentally in a down-fire reactor
43 located in Wroclaw University of Technology, as shown in Figure 1. The height of reactor is
44 1100 mm with an inner diameter of 200 mm. Two-stage electrical heating units are equipped to
45 ensure a maximum furnace temperature of 900 °C. The furnace temperatures are monitored by
46 thermocouples at two height levels. Two photosensitive elements are equipped at the top of the
47 reactor, one of them is installed vertically along the furnace (I) and the other one is installed with
48 an angle of 45° (II), to ensure the interior of the reactor is fully monitored. The investigation of
49 the ignition of the biomass particles is carried out in two steps. In the first step the luminous
50 emittance of the internal walls of the reactor is determined as the reference. Afterwards, the
51 sample is injected and the luminous emittance is measured and compared with the reference one.
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Once the ignition of biomass particles occurs, the heat released increases the temperature of the reactor walls and their luminous emittances, which is recorded computer controlled photosensitive elements. The ignition delay time is determined as a difference between the time of injection of the sample and the time when ignition occurs.

Straw, softwood, and torrefied softwood are studied in this work to compare their ignition delay times under varying conditions, and fuel properties of them are listed in Table 1. To investigate the effects of particle size on the ignition, samples with different particle sizes of each type fuel are prepared and tested at variable temperatures, and the ignition delay times of repeatable ignition cases are recorded. For each test, 0.1-gram sample is loaded in a visible loading tube, which is finally injected into the furnace by pressurized air once the expected furnace temperature is achieved and maintained as stable. The amount of air in the furnace chamber is sufficient for stoichiometric burning of the injected biomass particles. The flue gas is discharged via an outlet placed at the furnace top. The calibrations of photosensitive elements, temperature, and oxygen concentrations inside the reactor are repeated after each test completed.

Figure1.

Table1. Fuel properties

	Proximate analysis, wt%			Ultimate analysis, wt%						LHV^{db} (MJ/kg)
	$Moisture^{ar}$	$Volatiles^{ar}$	FC^{ar}	Ash^{ar}	C^{db}	H^{db}	O^{db}	N^{db}	S^{db}	
Straw	7.8	72.3	16.2	3.7	51.3	6.0	37.4	1.71	0.26	17.3
Softwood	2.6	82.3	14.9	0.2	49.3	5.9	43.8	0.76	0.10	18.0
Torrefied* softwood	1.4	81.3	17.1	0.2	53.9	4.4	40.6	0.76	0.10	19.8

* The torrefied biomass is produced by exposing the softwood particles in the oxygen-free furnace for 30 minutes at 250 °C.

2.2 Ignition temperature estimations

TG and DTG curves have been often employed to identify the ignition temperature and burnout temperature, which provides fundamentals of the fuel properties for analyses of the ignition phenomena discovered in the down-fire reactor. The characteristic temperatures obtained from the different methods are slightly different, but the values can be compared quantitatively as long as a consistent definition of these quantities is used. By analyzing TG and DTG curves, the ignition temperatures T_i of solid fuels are often identified as: 1) the temperature at which the combustion rate rises to 1 wt.% min⁻¹ at the start of a major combustion process [12]; 2) the

onset temperature of devolatilization and the maximum reactivity temperature (DTG_{max})[13]; 3) and also the temperature at which the weight loss curves in the oxidation and pyrolysis experiments diverge [12]. Due to concerns about the reliability of methods based on individual TGA run[14], in this work, the TG and DTG tests of all the studied fuel samples will be conducted and compared under inert (without oxygen presence) and oxidative (with oxygen presence) conditions, at various particle sizes.

2.3 Single particle model (SPM)

Combustion performance of biomass in a high temperature furnace has been comprehensively investigated using a single particle model in our previous work[15], by considering particle heating, drying, devolatilization, volatile combustion and char oxidation. Once exposed in the furnace at high temperatures, the biomass particle is heated up by the surrounding furnace wall and oxidizing agent via the radiation and convection approaches respectively. The temperature gradient is also considered, and the intraparticle heat transfer is governed by the conduction. The drying and devolatilization start when the local temperature inside particle reaches respective their reaction temperatures, which may occur simultaneously until the biomass particle is completely dried. The released amount of volatile, the release rate and the volatile species are highly dependent on the fuel type and heating conditions e.g. final temperature and heating rates, which theoretically affect the ignition behavior of biomass. Therefore, the ignition behavior of biomass could be predicted with the assistant of understanding the devolatilization performance.

In the model, it is assumed that the biomass particles are spherical due to the fine particles at sizes range of 60-800 μm . In addition, the drying process is assumed to be independent to the combustion process. The mass and energy equations presented below describe the evolution of volatile components:

$$\frac{m_v(t)}{m_{p,0}} = \int_0^t (\alpha_1 k_1 + \alpha_2 k_2) \exp(-\int_0^t (k_1 + k_2) dt) dt \quad (1)$$

$$\frac{\partial T_p}{\partial t} (\rho_M C_{P(M)} + \rho_{DB} C_{P(DB)} + \rho_{Char} C_{P(Char)} + \rho_{Ash} C_{P(Ash)}) = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 k' \frac{\partial T_p}{\partial r} \right) + \tilde{Q} \quad (2)$$

The two-competing model is employed to simulate the devolatilization process and predict the high temperature volatile yield. To accurately predict the effects of particles size on the devolatilization process, the particle size changes of biomass during the thermal conversions are comprehensively considered. More detailed descriptions about the model are available in our previous work [15]. Finally, considering comprehensively the sub-processes of particle heating,

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3 drying, and devolatilization, this model will be employed to predict the timescales of
4 devolatilization at varying degrees to help in better understanding of ignition behavior.
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7 **3 Results and Discussions**

8 **3.1 Combustion characteristics of biomass materials in TGA**

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10 TGA is very useful method to study fuel properties from a fundamental point of view, which
11 provides supportive information for analyzing ignition behaviour of solid fuels [16]. Three
12 biomass materials are studied in this work, including straw, softwood and torrefied softwood; all
13 of the biomass materials are milled and then selected as samples for testing. The TG and DTG
14 curves of studied three biomass materials under the air condition are shown in Figure 2.
15 Generally, the first peak of the combustion is attributed to the devolatilization of hemicellulose
16 and cellulose, which are more reactive chemical compounds of biomass than lignin [17]. It is
17 obvious that the straw has a higher reactivity than the softwood; thus with an increase of
18 temperature, the decomposition of straw biomass starts early and the first-peak in the DTG
19 curve is at 313 °C, while the softwood requires a higher temperature to initiate its thermal
20 conversions, and hence its first-peak in the DTG curve is at 352 °C.
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24 Torrefaction has been employed to improve the biomass fuel quality by releasing of its
25 hemicellulose and part of cellulose, alternating biomass fuel properties with enhanced energy
26 density and reduced reactivity in order to be close to that of coal. In this study, the torrefied
27 biomass is produced by exposing the softwood particles in the oxygen-free oven for 30 minutes
28 at 250 °C. In the TG curves, a delayed decomposition of the torrefied softwood is observed,
29 especially at the initial stage of devolatilization, indicating the hemicellulose was released during
30 torrefaction while the devolatilization is referred to the cellulose that has a lower reactivity than
31 hemicellulose. In addition, the first-peaks of softwood and torrefied softwood are overlapped at
32 352 °C, which was attributed to the cellulose that is the major component of softwood. And
33 therefore, the nature of biomass fuel combustion does not change significantly by torrefaction.
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49 **3.2 Thermal characteristics of softwood under air and N₂ conditions in TGA**

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51 The thermal characteristics of softwood under air and N₂ conditions are investigated in TGA,
52 the results are shown in Figure 3. There is a common approach to identify the ignition
53 temperature at which the deviation of mass losses in inert and oxidizing atmosphere is
54 observed[16]. From the comparison of the pyrolysis and combustion profiles of softwood, the
55 ignition mechanism can be estimated. The TG curves showed slight differences between the
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3 mass losses at oxygen-free and air conditions in temperature range up to ca. 400 °C. The similar
4 amount volatile released in the air condition to the case at the oxygen-free condition, indicating
5 the release of volatiles is primarily driven by the increase of temperature rather than the presence
6 of oxygen. The slight differences may be attributed to higher thermal conductivity of air than of
7 nitrogen, equal to 49.4 and 48.7 mW/m/K respectively at 1 MPa and 400 °C [18, 19]. At
8 temperatures above 400 °C, the mass loss in nitrogen changes slightly due to the slow process of
9 devolatilization, while in air it was observed a sharp drop of mass loss, due to oxidation of
10 remaining char. In the oxygen-free case, the total remained mass is converging to the sum of
11 fixed carbon and the inherent ash, while in air atmosphere it is similar to the amount of inherent
12 ash.
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20 The comparison of behaviour of fuels in an inert and an oxidative atmosphere indicates the
21 mechanism of ignition. For two investigated samples, at temperatures below 400 °C, the mass
22 loss takes place in the same way, both in oxygen-free and air atmospheres, thus according to
23 Arenillas et al. [16] the ignition is recognized as homogenous. As described by Arenillas et al.,
24 observed mechanism may be attributed to the composition of volatile compounds, which are
25 more stable than in heterogeneous ignition case, thus there are evolved in relatively high
26 temperatures where the char can react and thus the whole particle burns together.
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32 Moreover, the impacts of particle sizes on the thermal conversion processes of softwood in
33 TGA have also been investigated. In the tests, a slight difference was noticed when conducting
34 the pyrolysis and combustion process in TGA for varying sizes of softwood samples. Figure 3
35 listed the TG and DTG curves of two groups of softwood particles, 63-90 µm and 315-500 µm.
36 It is obvious that the corresponding temperatures of the first-peaks of either the combustion
37 process or the pyrolysis process are not affected when increasing the particle sizes, and
38 consequently the TGA results are failed to discover the impacts of particle size on the thermal
39 conversion behavior of biomass. However, it can be seen that the presence of oxygen can
40 accelerate the devolatilization process, and thus potentially have impacts on the ignition behavior.
41 A higher peak of devolatilization of small softwood particles than that of large softwood particles
42 shows large biomass particle has a lower reactivity, while the peaks of char oxidation are nearly
43 the same for large particles.
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Figure3.

3.3 Effects of biomass type on the ignition delay time

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3 As discussed in 3.2, the TGA results are failed to identify the effects of particle size on the
4 thermal behavior, which could be attributed to the low heating rates and the stationary of
5 biomass particles. Advanced ignition testing approach is thus required for understanding the
6 ignition behavior of different biomass and the impacts of particle sizes. As mentioned before,
7 ignition temperature is not a fundamental parameter of the fuel, which are affected by the
8 particle size, heating rate of the particle, and the surrounding atmosphere [4]. When a biomass
9 particle enters a pulverized fuel flame, it is rapidly heated to a final temperature that is far above
10 its ignition temperature. Therefore, the ignition delay times at varying temperatures will be of
11 interesting in this work, which becomes a key factor that can be referenced for biomass boiler
12 design and retrofitting, and also for optimization of the biomass combustion or co-firing
13 performance, by incorporating the transport phenomena and surrounding atmosphere.
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21 Figure 4 presents the impacts of fuel types on the ignition delay time of biomass. It is worth to
22 point out that Figure 4 only shows the cases with ignition occurred, while the tests without
23 detectable or repeatable ignitions are excluded. Generally, the ignition delay times of all the
24 biomass materials are getting shorter with increasing of the furnace temperature. In addition, it is
25 observed that, being injected into the furnace, softwood particles take a longer time to ignite
26 than the straw particles and this can be explained as the high reactivity of straw biomass that
27 promotes its ignition process. Specifically, the straw particles at sizes of 63-90 μm were
28 successfully ignited at temperature slightly over 500 $^{\circ}\text{C}$ and the corresponding ignition delay time
29 is 0.535 s at 508 $^{\circ}\text{C}$.
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36 The ignition delay times of softwood are ranged from 0.269 s at 665 $^{\circ}\text{C}$ to 1.085 s at 526 $^{\circ}\text{C}$, the
37 tests at furnace temperatures under 520 $^{\circ}\text{C}$ were failed to detect an ignition. The ignitions of
38 torrefied biomass are also conducted; however, the curve of its ignition delay times is crossed
39 with that of the raw softwood. According to their reactivity, the ignition delay time of the
40 torrefied biomass is expected longer than that of untreated biomass at the same temperature,
41 thus the ignition behavior of the raw and torrefied softwood are reasonable at temperatures
42 under 590 $^{\circ}\text{C}$. While at relative high temperatures, torrefied biomass shows a shorter minimum
43 ignition delay time than that of raw biomass, it could involve the change of mechanisms from
44 homogeneous ignition to heterogeneous ignition due to the high porosity after torrefaction
45 improves its char oxidation process and thus the ignition occurred at the particle surface. Further
46 studies on the effects of torrefaction on the biomass ignition mechanism are required.
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Figure 4.

3.4 Effects of particle size on the ignition delay time

Figure 5 (a) presents the impacts of particle sizes on the ignition delay time of biomass at the varying temperatures. It is clear that larger particles require high temperature to be ignited and the converging minimum ignition temperatures are increased when increasing the size of the biomass particles; this could be explained as the low reactivity of large biomass particle as discussed in the TGA results. The ignition of largest size particles of 630-800 μm were unable to be detected by photosensitive elements at a furnace temperature below 700 $^{\circ}\text{C}$. In addition, at a same furnace temperature, it takes a longer residence time to ignite the larger biomass particles. For example, 0.269 s will be taken to ignite the 63-90 μm softwood particles at 638 $^{\circ}\text{C}$; while 0.537 s is required to ignite the 315-500 μm softwood particles at the same temperature.

Figure 5(b) shows that the ignition delay times of three biomass materials with varying sizes at a particularly selected temperature of 650 $^{\circ}\text{C}$. It can be concluded from this results that the ignition of biomass is delayed when increasing its size; while vice versa to achieve a short ignition delay time for the same biomass material, an efficient approach is to reduce its particle size. These results will help to understand and control the processes of pulverized biomass combustion or co-firing with coal in coal-fired boilers, and therefore the biomass particle size can be optimized if the fuel properties and co-firing boiler configurations are known. The results can also be utilized to realize a promising biomass combustion performance by adjusting the size of biomass particles to match that of coal with aim of large percentage biomass co-firing in exiting pulverized coal boilers.

Figure 5.

3.5 Discussions of ignition and devolatilization

Biomass particle, when entering into the furnace chamber, is heated up rapidly to the furnace temperature, during which its thermal conversion process becomes very complicated due to the heating of the particle by its surrounding environment, drying, devolatilization, and the char oxidation. It is still in debate whether coal ignites homogeneously or heterogeneously [3], due to the challenge to identify it by experimental approaches. However, it has been advised by Zhang and Wall that the high volatile content in coal leads to a homogeneous ignition[2]. Compared to coal, biomass contains high amount of volatiles, for example, the volatile content in the studied softwood is over 80% on dry basis, and it is therefore reasonably assumed that the biomass ignition in this study is dominated by the homogeneous ignition mechanism. In addition,

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3 according to the TGA results (see 3.2), the ignition of softwood is identified as homogeneous
4 mechanism, which thus not begins until volatiles released. It is known that the released amount
5 and release rate of volatile are determined by the fuel types and the heating process, such as the
6 furnace temperature and heating rate. It is therefore interesting to discover the relationship
7 between the biomass ignition and its devolatilization process.
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11 The ignition delay times of softwood at 63-90 μm has been determined at varying furnace
12 temperature in the down-fire furnace and shown in Figure 6. An obvious trend is noticed that
13 the ignition time is getting shorter with increasing of furnace temperatures. On the other hand,
14 the released amount of volatiles increases with increasing of furnace temperature; while the
15 residence time determines the released amount of volatiles at certain temperatures, a shorter
16 residence time refers to less amount of released volatile. The degree of devolatilization can be
17 mathematically identified and defined as below:
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$$\varphi_{dove} = 1 - \frac{f_v}{f_{v,0}}$$

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27 Where f_v is the volatile content in the solid residuals and $f_{v,0}$ is the initial volatile content in the
28 raw biomass based on the standard proximate analysis.
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31 It is therefore interesting to understand the relationship between the ignition behavior of
32 biomass and the devolatilization process. The numerical model of combustion of single biomass
33 particle was previously developed in our previous work [15], which is able to predict the
34 timescales of varying degree of devolatilization. It should be pointed out that the prediction of
35 devolatilization time in the model is affected by the particle external and internal heating
36 processes.
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41 Figure 6 compares the timescales of ignition delay time, and the timescales of devolatilization at
42 the degrees of 10%, 20% and 30% respectively. It shows that biomass at low furnace
43 temperature requires more volatile released to be ignited and the impacts are very sensitive to the
44 devolatilization process that is determined by the furnace temperature. The optimized ignition
45 delay time is as quick as 0.26 s with 10% devolatilization degree at the furnace temperature of
46 660 °C. It can be predicted that, at a high enough furnace temperature, biomass could ignite
47 before the start of devolatilization, indicating a heterogeneous ignition is taken place at the
48 particle surface. Therefore, the ignition mechanism of biomass could be switched from
49 homogeneous ignition to the heterogeneous ignition. Obviously, the furnace temperature to
50 alternate the ignition mechanism will depend on the fuel type and particles size. This conclusion
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3 can be used to control and optimize the biomass combustion or co-firing performance based on
4 the ignition behaviors by modifying particle sizes and the local temperature in near burner zone.
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9 Figure 6.

10 **4 Conclusions**

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12 This paper investigated the ignition behaviour of biomass particles for optimization of co-firing
13 performance. Three types of biomass materials were studied including straw biomass, softwood
14 and torrefied softwood. Prior to the experimental investigations, TGA analysis of biomass fuels
15 has been performed to understand their ignition behaviours. Finally, the ignition behaviour
16 studies of biomass particles were conducted in a down-fire reactor.
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20 The TGA results in this work are failed to identify the impacts of particle size on the ignition
21 behavior of biomass using TGA although such researches have been attempted previously,
22 which is majorly limited by its low heating rate and stillness of particles. However, it has been
23 observed that, at the same furnace temperature, larger particles of biomass require long time to
24 start its ignition than a smaller particle according to the testing results in down-fire reactor. TGA
25 approach has been used to determine the ignition temperature by identifying the diverse point of
26 TG curves of biomass with and without the presence of oxygen. In this work, although
27 acceleration of devolatilization rate of softwood is observed by presenting the oxygen but its TG
28 curve is almost overlapped with that of pyrolysis case, accordingly it is concluded that softwood
29 is ignited homogeneously. Furthermore, the ignition delay times of all biomass materials are
30 getting shorter when increasing furnace temperature. In addition, it is observed that, after
31 injected into the furnace, softwood particles take a longer residence time to be ignited than straw
32 particles, which agrees well with their reactivity analysis in TGA. While the ignition delay time
33 curve of torrefied softwood is crossed with that of softwood, it could be explained as the change
34 of mechanisms from the homogeneous to heterogeneous ignition, further studies on this ignition
35 mechanism are required. In addition, at a high enough furnace temperature, the ignition of
36 biomass will be started directly from the particle surface without requiring the devolatilization to
37 take place, it is thus concluded the ignition mechanism of biomass is highly dependent to the
38 furnace temperature and the devolatilization degree. In general, the ignition behavior and
39 consequent combustion performance of biomass are able to be modified by adjusting its
40 devolatilization degree with controllable the biomass particle size and the surrounding gas
41 temperature, and eventually the processes of pulverized biomass combustion or co-firing with
42 coal in coal-fired boilers can be optimized.
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Acknowledgement

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Nomenclature

Symbols

f	The content in the solid residuals
k	Reaction rate constant expressed in Arrhenius form, (kg/m ² -Pa-s)
k'	Thermal conductivity (W/m-K)
m	Mass, (g)
\tilde{Q}	Reaction heat absorbed by solid remains (J)
r	Particle radius (m)
R	gas universal constant, 8.3143 J/(mol-K);
T	Temperature, (K)
α	Volatile yield factor

Subscripts

DB	Dry biomass
devo	Devolatilization
M	Moisture
p	Particle
v	Volatile
0	Initial value
1	Refers low temperatures
2	Refers high temperatures

References

- [1] <https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E21%20Biomass%20Co-firing.pdf>.
- [2] D.-k. Zhang and T. F. Wall, "An analysis of the ignition of coal dust clouds," *Combustion and Flame*, vol. 92, pp. 475-480, 1993/03/01 1993.
- [3] H. Katalambula, J.-i. Hayashi, T. Chiba, K. Kitano, and K. Ikeda, "Dependence of Single Coal Particle Ignition Mechanism on the Surrounding Volatile Matter Cloud," *Energy & Fuels*, vol. 11, pp. 1033-1039, 1997/09/01 1997.

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3 [4] T. Grotkjær, K. Dam-Johansen, A. D. Jensen, and P. Glarborg, "An experimental study of biomass
4 ignition☆," *Fuel*, vol. 82, pp. 825-833, 5// 2003.
- 5 [5] J. M. Jones, A. Saddawi, B. Dooley, E. J. S. Mitchell, J. Werner, D. J. Waldron, *et al.*, "Low
6 temperature ignition of biomass," *Fuel Processing Technology*, vol. 134, pp. 372-377, 6// 2015.
- 7 [6] J. Rianza, L. Álvarez, M. V. Gil, R. Khatami, Y. A. Levendis, J. J. Pis, *et al.*, "Ignition behavior of coal
8 and biomass blends under oxy-firing conditions with steam additions," *Greenhouse Gases: Science and
9 Technology*, vol. 3, pp. 397-414, 2013.
- 10 [7] A. Toptas, Y. Yildirim, G. Duman, and J. Yanik, "Combustion behavior of different kinds of torrefied
11 biomass and their blends with lignite," *Bioresource Technology*, vol. 177, pp. 328-336, 2// 2015.
- 12 [8] J. Li, A. Brzdekiewicz, W. Yang, and W. Blasiak, "Co-firing based on biomass torrefaction in a
13 pulverized coal boiler with aim of 100% fuel switching," *Applied Energy*, vol. 99, pp. 344-354, 11//
14 2012.
- 15 [9] Y. Liu, M. Geier, A. Molina, and C. R. Shaddix, "Pulverized coal stream ignition delay under
16 conventional and oxy-fuel combustion conditions," *International Journal of Greenhouse Gas Control*,
17 vol. 5, Supplement 1, pp. S36-S46, 7// 2011.
- 18 [10] B. Goshayeshi and J. C. Sutherland, "A comparison of various models in predicting ignition delay in
19 single-particle coal combustion," *Combustion and Flame*, vol. 161, pp. 1900-1910, 7// 2014.
- 20 [11] I. Trabadelá, "Ignition of suspensions of coal and biomass particles in air and oxy-fuel for Carbon
21 Capture and Storage (CCS) and climate change mitigation," PhD, School of Engineering, University of
22 Edinburgh, Edinburgh, 2015.
- 23 [12] C. a. Wang, X. Zhang, Y. Liu, and D. Che, "Pyrolysis and combustion characteristics of coals in
24 oxyfuel combustion," *Applied Energy*, vol. 97, pp. 264-273, 9// 2012.
- 25 [13] C. Wang, F. Wang, Q. Yang, and R. Liang, "Thermogravimetric studies of the behavior of wheat straw
26 with added coal during combustion," *Biomass and Bioenergy*, vol. 33, pp. 50-56, 1// 2009.
- 27 [14] Y.-s. Fan, Z. Zou, Z. Cao, Y. Xu, and X. Jiang, "Ignition Characteristics of Pulverized Coal under High
28 Oxygen Concentrations," *Energy & Fuels*, vol. 22, pp. 892-897, 2008/03/01 2008.
- 29 [15] J. Li, M. C. Paul, P. L. Younger, I. Watson, M. Hossain, and S. Welch, "Prediction of high-temperature
30 rapid combustion behaviour of woody biomass particles," *Fuel*, vol. 165, pp. 205-214, 2/1/ 2016.
- 31 [16] A. Arenillas, F. Rubiera, B. Arias, J. J. Pis, J. M. Faúndez, A. L. Gordon, *et al.*, "A TG/DTA study on
32 the effect of coal blending on ignition behaviour," *Journal of Thermal Analysis and Calorimetry*, vol.
33 76, pp. 603-614, 2004.
- 34 [17] E. Biagini, F. Barontini, and L. Tognotti, "Devolatilization of Biomass Fuels and Biomass Components
35 Studied by TG/FTIR Technique," *Industrial & Engineering Chemistry Research*, vol. 45, pp. 4486-
36 4493, 2006/06/01 2006.
- 37 [18] E. W. H. Lemmon, M. L., "NIST Reference Fluid Thermodynamic and Transport Properties Database
38 (REFPROP): Version 9.1," ed. Gaithersburg: NIST Standard Reference Database 23, 2013.
- 39 [19] E. W. Lemmon and R. T. Jacobsen, "Viscosity and Thermal Conductivity Equations for Nitrogen,
40 Oxygen, Argon, and Air," *International Journal of Thermophysics*, vol. 25, pp. 21-69, 2004.

41 Figure Captions:

42 Figure 1. A schematic of the ignition test reactor

43 Figure 2. Combustion characteristics of 3 biomass materials in TGA (a) TG curves; (b) DTG curves

44 Figure 3. Thermal characteristics of softwood under air and N₂ conditions in TGA (a) TG curves; (b) DTG curves

45 Figure 4. Effects of fuel types on the biomass ignition behaviour

46 Figure 5. Effects of particle sizes on the biomass ignition behaviour (a) softwood at varying temperatures; (b)
47 various biomass materials at 650 °C

48 Figure 6. Volatile release times vs. ignition delay times

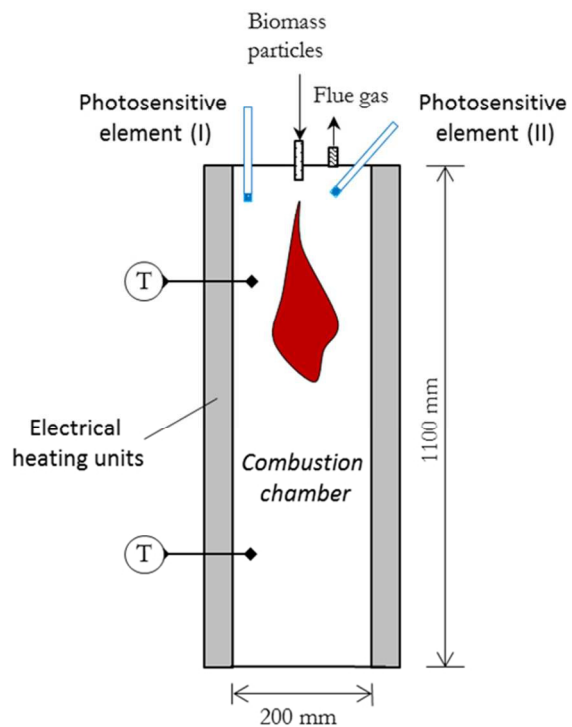


Figure 1. A schematic of the ignition test reactor
254x190mm (96 x 96 DPI)

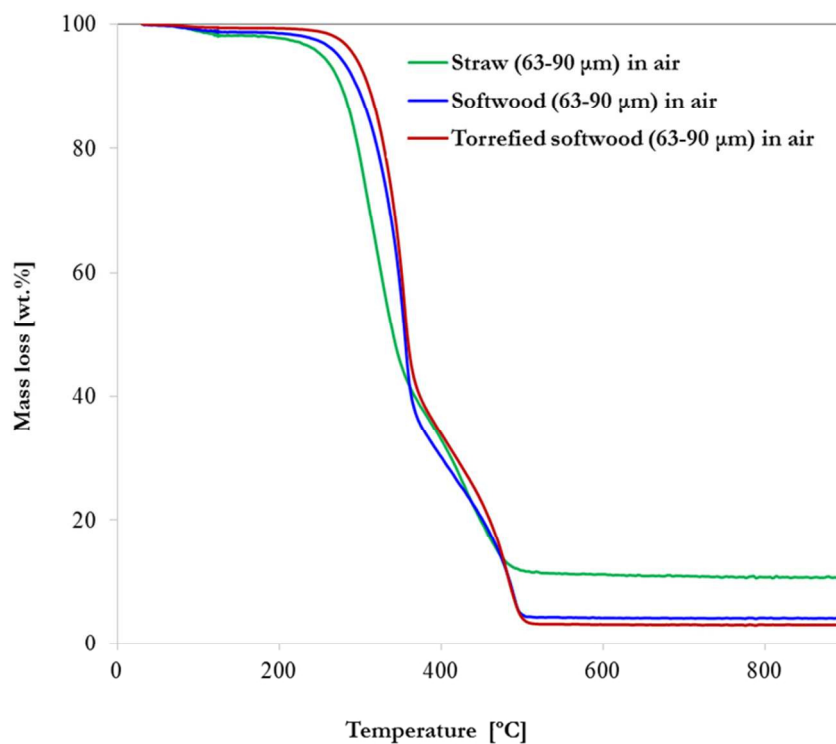


Figure 2. Combustion characteristics of 3 biomass materials in TGA (a) TG curves; (b) DTG curves
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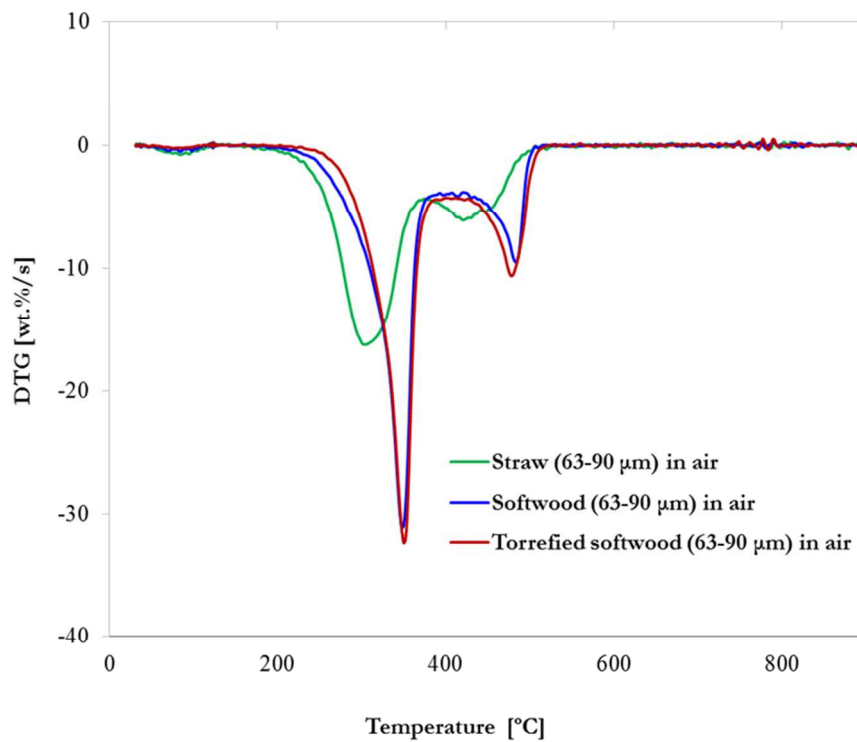


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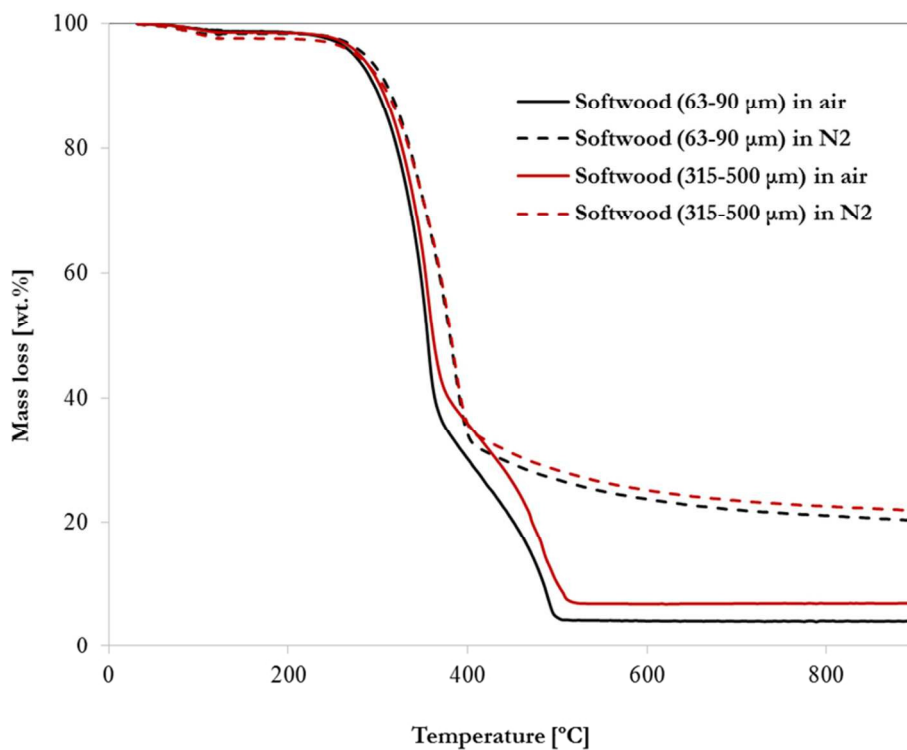


Figure 3. Thermal characteristics of softwood under air and N2 conditions in TGA (a) TG curves; (b) DTG curves
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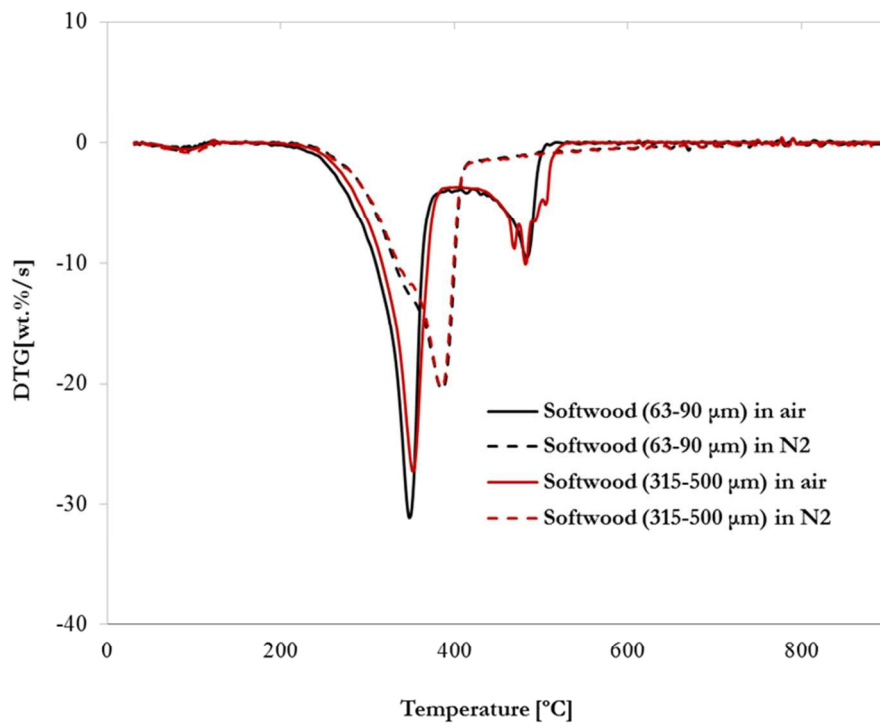


Figure 3. Thermal characteristics of softwood under air and N₂ conditions in TGA (a) TG curves; (b) DTG curves
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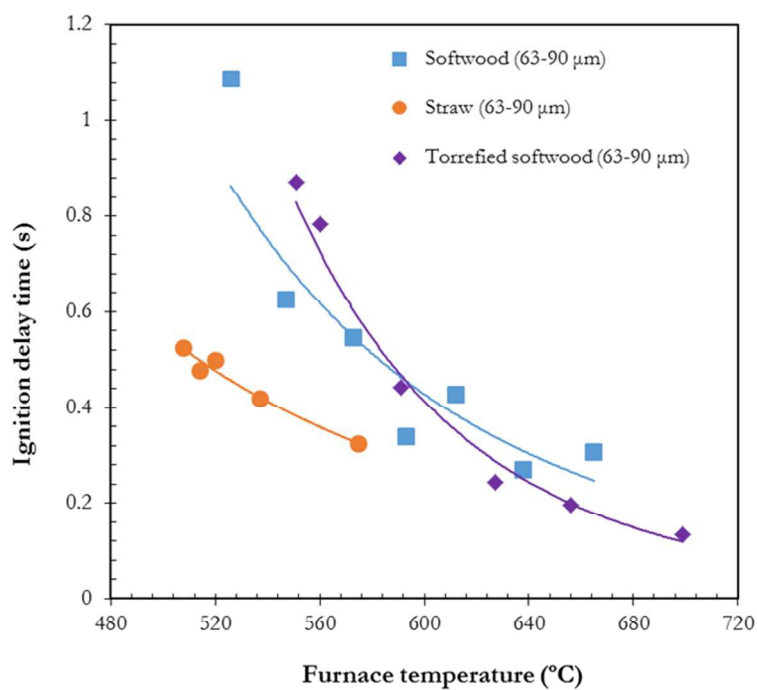


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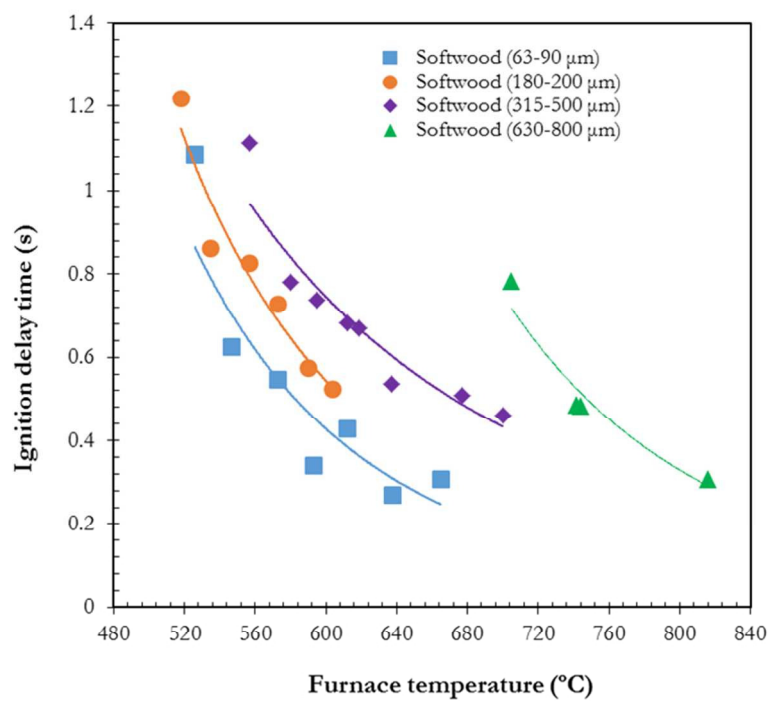


Figure 5. Effects of particle sizes on the biomass ignition behaviour (a) softwood at varying temperatures;
(b) various biomass materials at 650 °C
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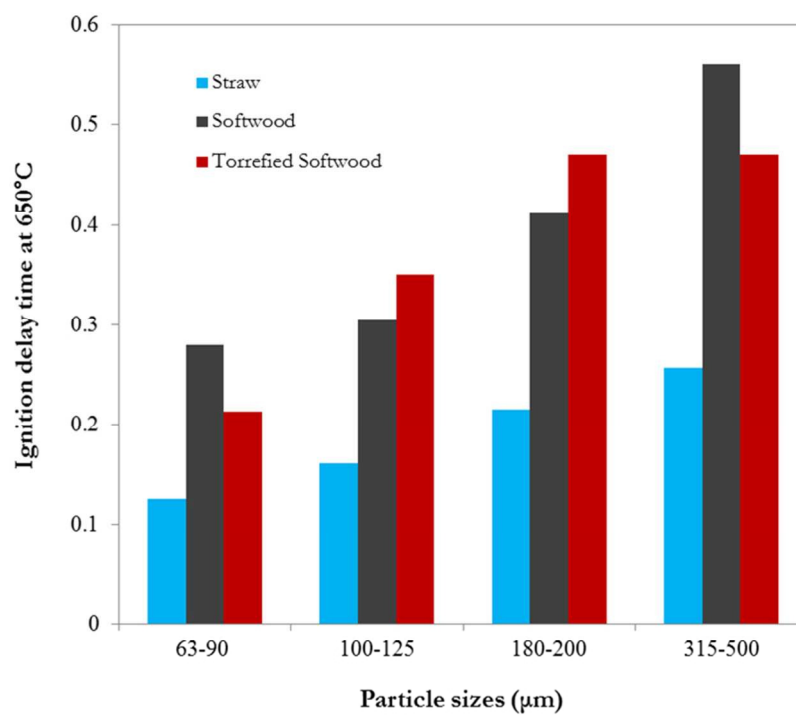
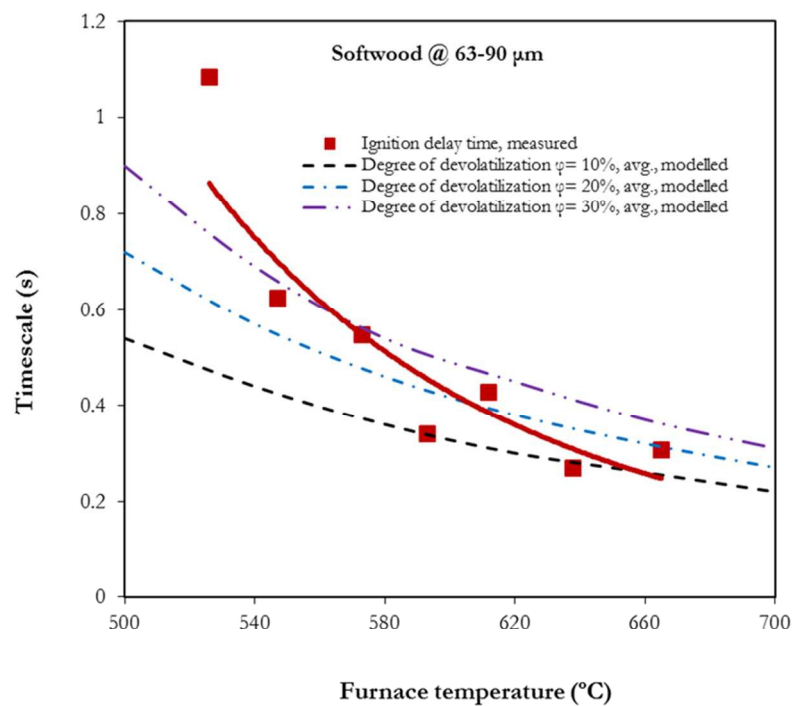


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