Ignition Behavior of Bio-Coke (Highly Densified Biomass Fuel) in High-Temperature Air Flows*

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Abstract
The ignition behavior of a newly developed biomass briquette, Bio-coke (BIC), is investigated. The fuel has unique features such as economical advantages for its versatility of biomass resources, high volumetric calorific value because of its high density (1300 kg/m³; twice or more than that of ordinary wood pellets) and high mechanical strength. The ignition characteristics of cylindrical BIC blocks (48 mm in diameter and 85 mm in length), important when using the fuel in actual combustion furnaces, are investigated in high temperature air flows (473-873 K, 550-750 NL/min.). In the experiments, preheated air is blown onto the bottom surface of BIC cylinders and the ignition behavior of the bottom surface is observed monitoring the surface temperature as well as the time dependent mass loss rates. The results show two ignition modes; (1) solid surface ignition preceding gas-phase ignition in high air temperature conditions (T ≥ 598K), and (2) gas-phase ignition accompanied by simultaneous surface ignition occurring at relatively low air temperature conditions. The appearance of each mode depends on the preheated air supply condition in terms of the air temperature, flow velocity, and moisture content of the fuel. The rate of evolution of volatile gases is closely correlated with the temperature distribution inside the BIC briquette which depends on the heating rate, implying that variations in the temperature distribution inside the fuel could be one reason for the appearance of the observed ignition modes. It is suggested that the temperature distribution inside the fuel has to be taken into account in the control of the ignition behavior of BIC briquettes.

Key words: Biomass, Ignition, Combustion, Biocoke, High Temperature Air

1. Introduction
Biomass utilization for energy generation has attracted much attention with present day concerns about energy and global warming. Biomass is a renewable fuel, and it is considered that the combustion of biomass fuel will promote "carbon-offset" and contribute to climate protection. There are problems, however, in utilizing biomass as a fuel, including the low calorific value per unit volume, and the special treatment required before utilization to transport and store economically. It is also difficult to control the burning rate in combustion equipment since raw biomass fuel may be inhomogeneous and may have a too
high burning rate. Pelletizing and briquetting of biomass are well-known densification treatments to increase the energy density. This kind of treatment also reduces transport and storage costs and facilitates control of the burning status because the homogeneity is improved and the combustion becomes quite stable. However, biomass pellets and biomass briquettes still have two major unavoidable disadvantages hindering their more widespread use [1]. The first issue is to be price competitive with conventional fossil fuels including in distribution costs. Second, the need for development of combustion equipment to burn the fuel with high efficiency and low pollutant emissions.

To get around these disadvantages, a newly-developed type of fuel has been proposed, the so called “Bio-coke (BIC)” [2-3]. The highly densified biomass BIC is manufactured with high compression and at moderate temperatures, and this alternative fuel will be investigated below in the present study. Bio-coke (BIC) has high mechanical strength and is able to withstand the compressive stress in blast furnaces and has been successfully shown [2] to be a potential alternative to coal coke. The BIC briquettes can be manufactured in a wide range of sizes, also large dimensions (48 mm in diameter and 85 mm in length) and with densities higher (1300 kg/m$^3$) than ordinary wood pellets (600 kg/m$^3$) [4]. As a result the combustion time of the fuel [5-6] enables a longer heat release with a small number of fuel loadings, resulting in a better overall performance than existing biomass fuels.

There are also economic advantages with BIC, as it can be produced from any biomass resource including wood, biomass residue and biomass waste, and therefore, can be supplied at low cost from residue and waste from households and factories, or even weeds can be used as the fuel resource. Further, it has relatively low transport and storage costs due to its high volumetric calorific value and high mechanical strength, and it is expected that this new fuel will be used in blast furnaces as well as in stoves and boilers. However, there has been little systematic study on the combustibility of BIC, especially of the ignition process. Ignition and the subsequent combustion characteristics in high temperature air flows are particularly important, since this is the standard operating mode employed in a variety of combustors. This study, therefore, investigated the ignition and subsequent combustion of BIC in very hot, preheated air. The effect of air temperature and air flow rates on combustion behavior and the internal temperature profile in BIC has been simultaneously examined to understand details of the process of its combustion. The main objective is to gain a better understanding of the basic combustion characteristic of BIC and to find ways to control the combustion and other behaviors.

In the ignition and combustion process of a large fuel block, the rate of evolution of volatiles may depend on a temperature distribution inside the fuel as the rate of pyrolysis depends on heat transfer processes [7]. It was assumed that the temperature distribution inside the fuel depends on the heating rate and fuel properties, and that the ignition and combustion behavior would be influenced by these two factors. The BIC briquettes considered in this study are physically large and have a high density as mentioned above making it important to investigate the influence of these characteristics on the pyrolysis and combustion behavior. There are studies [8-11] of the pyrolysis of large biomass fuel volumes, however there has been little investigation of the combustion processes involved. One such investigation was reported by Ouedraogo et al. [12], presenting a so called "shrinking core model" for the pyrolysis, devolatilization and char oxidation of solid biomass fuel under quasi-steady-state combustion. However, this work was based on steady-state and non transient processes with the likely spontaneous ignition and subsequent combustion mode for this kind of combustion discussed.

Changing of the preheating temperatures as well as air flow rates are the main experimental parameters considered in the investigation to be reported here. These parameters were selected to become able to understand the combustion characteristics of the densified biomass fuel in actual combustion equipment including boilers and furnaces, the
influence of heating rates, the air temperature and air flow rates, on ignition and combustion behavior in high temperature air flows need to be established. Some research [8, 13-14] has investigated the ignition and combustion of biomass fuel in air without controlling the air flow rate. However, as the mixing and heating processes of the evolved gas and air is strongly affected by the surrounding air flow conditions, the ignition and subsequent combustion would also be affected by the conditions of the air flow. In this way, the effect of air temperature and air flow rate on ignition mode is an important aspect to elucidate. In addition, the effect of the moisture content of the fuel is also examined.

2. Experimental

2.1 Test Sample (BIC of Japanese knotweed)

Reynoutria japonica (Japanese knotweed) collected at Shimokawa-cho in the north of Japan was selected as the biomass resource for this study as it is considered a weed with no particular use, and therefore, may be viewed as the kind of typical BIC low cost raw material that would be available in rural locations. The relevant basic properties of the Japanese knotweed used are listed in Table 1. The gross calorific value is equal to 17890 kJ/kg; it is similar to wood pellets [4]. The detailed procedures for making BIC are reported elsewhere [15], briefly, harvested Japanese knotweed is pulverized, stuffed into cylindrical molds, pressed and heated simultaneously, and subsequently cooled to room temperature. After cooling, the cylindrical solid BIC briquette is removed from the mold. Biomass consists of cellulose, hemicellulose and lignin, and the lignin enhances the binding characteristics of the densified briquettes during heating, as lignin has a low melting point. When biomass is heated, lignin softens and may melt and this results in thermosetting [16]. In addition, the furfural derived from hemicellulose also contributes to the self-bonding properties [17]. For biomass, the densification proceeds at moderate temperatures and pressures and the resulting product in the case of the BIC briquettes is a large block of biomass with high mechanical strength and high density.

The dimensions of the BIC briquettes used in the present study are 48 mm in diameter and 85 mm in length. While the BIC has high mechanical strength, a distinctive property with respect to the combustion characteristics is its high density (1300 kg/m³ versus 600 kg/m³ [4] for wood pellets).

<table>
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<th>Table 1 Basic properties of untreated Japanese knotweed as harvested</th>
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<td>GCVa [kJ/kg]</td>
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a : Gross Calorific Value

2.2 Ignition and Combustion Experiments

A schematic outline of the experimental set up in the study here is shown in Fig.1. It consists of (a) a combustion chamber (100 mm inner diameter, 293 mm long), (b) an air heater, (c) a scale for measuring the mass loss of the BIC, (d) an infrared camera which monitors the bottom surface temperature of the BIC, (e) a digital video camera, and (f) thermocouples to measure the gas temperatures near the top and bottom edges of BIC.

A stainless steel bar (8 mm outer diameter) is screwed into the top of the BIC and this is suspended from an arm of the fulcrum. The BIC sample is located at the center of the
combustion chamber. Air is metered and subsequently heated by the electric heater and blown onto the bottom surface of the BIC. An R-type thermocouple (0.3 mm diameter) is employed to measure the gas temperatures near the top and bottom edges of the BIC. The junctions are located about 1 mm from the respective edges. The air supply temperature is determined by monitoring the temperature at the exit of the electric heater. The mass loss of the sample is monitored by a mechanical scale (SHIMADZU, UX4200H: minimum scale value 0.01 g).

Temperature changes at the bottom surface of the BIC are observed by the infrared camera (NEC Sanei, TH6200R, 8-14E-06 m, below 1273 K) through a Zn-Se glass window. The maximum temperature of the BIC bottom surface is termed the "BIC bottom surface temperature". The ignition and combustion behavior are recorded by the digital video camera (SONY DCR-TRV900) through quartz glass windows. The air temperature and air flow rate are varied within the range of 473-873 K and 550-750 NL/min., respectively.

Prior to the combustion experiments, the emissivity of the BIC bottom surface is determined based on temperature measurements by the thermocouple. Because the changes in the projection area of the BIC subjected to the air flow are considered small (no more than about 14% to the initial bottom surface area) during the experiments, the influence of changes in the flow momentum on the measurement of the mass loss is ignored.

3. Results and Discussion

3.1 Thermo Gravimetric Analysis

Prior to the combustion experiments with the experimental setup described above (Fig.1), thermo gravimetric analyses were carried out to understand the thermo-chemical characteristics of the BIC. Here, 20 mg specimens of the pulverized BIC extracted from the bottom center (bottom surface) of the BIC, which is to be exposed to the heated air in the combustion experiments described later, were heated by a radiant heater with a heating rate of 5 K/min and the mass loss of the specimen was measured in an ULVAC TGD-5000 thermo-balance.

Figure 2 shows the results of the thermo gravimetric analysis both in air and in a nitrogen atmosphere. From the results the water content may be estimated to be about 10 wt% due to the mass loss observed below 400 K. The content of fixed carbon can be estimated at about 13 wt% from the difference between the mass losses in N2 and air at around 900 K. The content of ash is approximated about 7 wt%, and therefore, the content of volatile matter can be estimated as 70 wt%.
From the comparison between the curves for air and nitrogen, it is found that differences caused by oxidation appear when the temperature exceeds around 450K.

3.2 Effect of Air Temperature on Ignition Behavior

In the ignition and the combustion experiments, the BIC sample was inserted into the combustion chamber after the air flow conditions had stabilized. Reynolds number of the heated air flow which is concerned with combustion duct ranges from 4800 to 5800 in this study. From the results of gas temperature measurement, it is assumed that the temperatures of air flow around the BIC are uniform in the period of the heating by the airflow. Figure 3 shows the changes in the unburnt fraction, bottom surface temperature of the BIC, and gas temperature near the bottom edge of the BIC in a hot air flow of 598 K (550 NL/min.). The abscissa shows the heating period of the BIC so that the time "0" means the moment when the sample is exposed to the hot air flow. In this study, the time of rapid temperature rise on the BIC bottom surface without flaming is defined as the "solid surface ignition", and can be observed at about 9 minutes in Fig.3. The time when luminous flames appear and the resulting instantaneous temperature rise observed in the gas phase near the BIC is defined as "gas-phase ignition", and can be observed at about 17 minutes in Fig.3. These ignition delay times are indicated by arrows in the figure.

In this study, two modes of ignition of the BIC were observed. In the high temperature air (defined as \( T_a \geq 598 \text{ K} \) in this paper) as shown in Fig.3, solid surface ignition precedes the gas-phase ignition (Mode 1). As shown in the figure, early in the exposure there is a slight decrease in unburnt fraction, which can be ascribed to dehydration of the BIC briquette. Solid surface ignition occurs when the exposure time reaches about 9 minutes. The bottom surface of the BIC turns red and a sharp temperature increase is observed. The solid surface combustion causes the decrease in unburnt fraction and continues until 17 minutes, and then the gas-phase ignition occurs. The gas-phase combustion continued for 11 minutes before the sample fell from the holder.

In the low temperature air (\( T_a \leq 573 \text{ K} \), 550 NL/min.) as shown in Fig.4, there is a completely different ignition behavior; the gas-phase ignition is observed simultaneously with the solid surface ignition (Mode 2). The BIC is heated by the hot air flow for a long duration, 38 minutes, and there is a slight decrease in unburnt fraction. After the simultaneous gas-phase ignition and solid surface ignition the gas-phase combustion continued for 7 minutes here.
The rate of increase in the BIC surface temperature right before solid surface ignition is determined by calculating the gradient of the approximate line which fits the data for the 0.75 minutes in the period before the sharp temperature increase was observed at the BIC surface, and summarized in Fig.5. The increase in the BIC surface temperature may be qualitatively correlated with the surface oxidation of the BIC. As Williams et al. [19] assumed, the chemical reaction rate of the BIC surface oxidation can be assumed to follow an Arrhenius form: 

$$k = A \exp(-E/(RT))$$

Here, $k$ a rate constant, $A$ a frequency factor, $E$ an activation energy, $R$ a gas constant and $T$ a temperature, respectively. This is the reason why the ordinate of Fig.5 shows a logarithmic rate of increase of the BIC surface temperature ($\Delta T/\Delta t$; $\Delta T$ and $\Delta t$ the changes in temperature and time, respectively).

In Fig.5, it is seen that all the plotted data obtained by the experiments (blank circles) can be well-approximated to the approximation line (solid line). And the rate of increase in the BIC surface temperature increases with increasing air temperature. This result suggests that the surface oxidation reaction is enhanced with increased air temperature.

The temperatures of the BIC surface and the gas near the BIC immediately before the gas-phase ignition are plotted in Fig.6. The gas temperatures near the BIC are measured at two locations near the top and bottom edges of the BIC as indicated in Fig.1. Here, each temperature is obtained by calculating the average for the 0.75 minutes in the period before the sharp temperature increase was observed in the gas-phase.

The dashed line in Fig.6 shows the temperature of 523 K and the plotted data indicate the temperatures where gas-phase ignition occur. From Fig.6, it is found that the temperature of 523 K is sufficiently high to ignite the mixture of the evolved gas and air because gas-phase ignition occurred even in the condition at 523 K. In the high temperature air ($T_a \geq 598$ K), it is found that the gas-phase ignition occurs well above 523 K and this suggests that the gas-phase ignition would not occur immediately when the BIC surface and gas temperatures reach temperatures higher than 523 K. Both the temperatures and an adequate supply of flammable mixture, i.e. enough evolved gas near the BIC block, are needed to cause the gas-phase ignition. Therefore, this result implies that the gas-phase ignition is influenced more strongly by the amount of evolved gas than by the temperature in the high temperature air.
3.3 Ignition Modes

To investigate the influence of heating rate (air temperature) on the temperature distribution inside the BIC at the beginning of heating, this section performs a numerical calculation to understand further details of ignition phenomena observed here. The basis for the numerical model is shown in Fig.7. Cylindrical coordinates are employed. The BIC is located at the center of the furnace, in which the furnace wall is regarded as adiabatic. The air flow which is assumed to have uniform temperature \(T_a\) and velocity \(V_a\) distributions is supplied from the bottom of the furnace, and form stagnation-point flow at the BIC bottom surface, then pass up along the side of the BIC.

The calculations take into account equations of mass conservation, momentum in the \(r\) and \(z\) directions, and the energy in the gas- and solid-phases in a time-dependent form, and include an equation of state for ideal gas. The heat transfer between air and the BIC surface (bottom and side), and the thermal conduction inside the BIC are considered, whereas radiation heat transfer is ignored. The heat transfer coefficients of the gas-solid interface are determined by the literature [20-21]. Nusselt number for the front face of the BIC is given by an average one for a stagnation plate [20]. Nusselt number for the side face of the BIC is given by one as a function of local Reynolds number for a laminar flow along a flat plate [21]. The thermal conductivity and the specific heat of the BIC are estimated by referring to Cozzani et al. [22] for cellulose, lignin and hemicellulose with the values derived from wood. Decomposition, evaporation and other reactions are ignored in this calculation. The temperature distributions for air temperatures of 523 K and 673 K are compared for the same air flow rate (550 NL/min.).

The calculated transitions in the temperature distribution on the center axis near the bottom surface of the BIC are shown in Fig.8 (a) at \(T_a = 673 \text{ K}\) and (b) \(T_a = 523 \text{ K}\). In the high temperature air (Fig.8 (a)), the surface temperature rises rapidly and the temperature distribution near the BIC surface has a steep gradient while the temperature at the inner part of the BIC (20 mm from the surface) remains low. In the low temperature air (Fig.8 (b)), the BIC surface temperature shows moderate values, not as high as the BIC surface temperature in the high temperature air even after 40 minutes and the heated layer of the BIC extends further toward the inner part of the BIC with time increases. It is confirmed that the trend of temperature change with time in \(r\) direction is similar to that in \(z\) direction, that is, the low temperature air also gives a broad temperature distribution inside the BIC in \(r\) direction. Since the region where the temperature exceeds the gas evolution temperature can be assumed to release evolved gas, a BIC briquette with a thick heated layer will release larger volumes of evolved gas, while a BIC with a thin heated layer will release less evolved gas.
Therefore, in the high temperature air (Fig. 8 (a)), the evolved gas from the BIC at the beginning of heating is not sufficient to ignite the gas-phase, even when the surface temperature has increased high enough to ignite in the solid-phase. In the low temperature air (Fig. 8 (b)), the surface ignition will occur later because of the low surface temperature and here the BIC block has been heated longer and will ignite the gas-phase when enough evolved gas is available.

Around the moment of ignition, the gas evolution rate can be assumed as the mass loss rate, i.e. the gradient of the curve in Fig. 3 and 4. From the results as indicated in Fig. 3 (at 17 minute) and Fig. 4 (at 38 minute), the mass loss rates of the BIC are 22.6 g/min. in the high temperature air (598 K) and 28.7 g/min. in the low temperature air (523 K), respectively. This fact suggests that the gas evolution rate in the low temperature air is larger than that in the high temperature air at the moment of ignition initiation. Thus, the differences in the temperature distribution inside the BIC and the rates of change with time could be reasons why the BIC has two modes of ignition.

According to Bryden [8] and Hagge [11], wood pyrolysis can be divided into three regimes by using Biot numbers \( Bi = \frac{hL}{\lambda} \), heat transfer coefficient \( h \), characteristic length \( L \) and thermal conductivity \( \lambda \); (1) thermally thin \( (Bi < 0.2) \), (2) thermally thick \( (0.2 < Bi < 10) \) and (3) thermal wave region \( (Bi > 10) \). Concerning Biot numbers, the BIC in the present study is classified in the “thermally thick” regime, at which \( Bi \) of the BIC is calculated around 2.5 by using the thermal conductivity derived from the literature [22]. Although some researchers [11, 23-24] have investigated the pyrolysis and combustion behavior of a large biomass block which is in the thermally thick regime, the ignition process was not taken into account in their studies. Since they did not focus on the ignition behavior of “thermally thick” biomass blocks, the two modes of ignition which is found in the present study have not been pointed out.

As the density \( \rho \) of BIC is much higher than that of the other densified biomass fuel [4], the heat capacity \( \rho C \) (specific heat \( C \)) of BIC is also larger than other biomass fuels. This large heat capacity causes it to take a long time to heat up its interior, and it prolongs gas evolution and gas-phase ignition. From the results of the present study, it is suggested that the influence of heating rate on the surface temperature and the amount of gas evolution,
which are closely correlated with the time-dependent temperature distribution inside the BIC, have to be taken into account in predicting the ignition process of the BIC due to its high density and resulting high heat capacity.

3.4 Effect of Air Flow Rate and Moisture Content of BIC on Ignition Behavior

The effect of air flow rate on the ignition behavior of the BIC was experimentally investigated. When the air flow rate is 750 NL/min., which is higher than the standard condition (550L/min.), solid surface ignition preceding the gas-phase ignition (Mode 1) occurs even when the air temperature is 523 K, whereas solid surface ignition doesn't precede (Mode 2) with 650 NL/min. as shown in Fig.9. The occurrence of surface ignition at higher air flow (750 L/min.) is explained by the increase in the heating rate of the BIC. From the results of the thermo gravimetric analysis (Fig.2), it is supposed that the oxidation of BIC would proceed above around 450K. Demirbas [25] also reported that the ignition temperatures of some biomasses are around 470K. It is considered that the rapid temperature rise due to the larger heat transfer causes surface oxidation before release of the evolved gas from the BIC inside and it results in the surface ignition preceding the gas phase ignition. Namely, the time dependent profile of the evolved gas from the BIC inside determines whether which ignition mode occurs.

The influence of the moisture content of the BIC on the ignition behavior of the BIC was experimentally investigated. The BIC which is heated and dehydrated in an electric furnace at 473 K for 2 hours and then cooled to room temperature, termed dried-BIC below, was employed for the combustion experiments. In this treatment, the dried-BIC lost about 7.5 % of its weight, which corresponds to three-fourths of the moisture content of the untreated BIC. The ignition mode of the dried-BIC was investigated and was compared to that of the untreated BIC in this study. The changes in the BIC surface temperatures, the gas temperatures near the bottom edge of the BIC and the unburnt fractions of the BIC in the conditions of 573 K (550 NL/min.) with the untreated BIC and with the dried-BIC are shown in Figure 10 (a) and (b), respectively.

For the untreated BIC (Fig.10 (a)), sharp increases in the surface temperature and the gas temperature are simultaneously observed, this indicates the surface ignition and the gas-phase ignition occur simultaneously (Mode 2). For the dried-BIC (Fig.10 (b)), the sharp
increase in the surface temperature precedes the sharp increase in the gas temperature, this indicates the solid surface ignition precedes the gas-phase ignition (Mode 1). The thermal conductivity of the sample becomes smaller by the dehydration [26] and the heat capacity decreases. The heat required to vaporize the water in the sample is lower in the dried-BIC than in the untreated BIC. Therefore, the surface temperature rises rapidly and the surface ignition occurs more easily with the dried-BIC than with the untreated BIC. It is also found in Fig.10 that the time the gas-phase ignition occurred with the dried-BIC (about 18 minutes) is longer than that with the untreated BIC (about 15 minutes). Although this may suggest the decrease in gas evolution rate and the decrease in the thickness of heated layer with decreasing the moisture content, further investigation is needed to understand the influence of the moisture content on the thermal diffusivity, \( \alpha = \lambda / (\rho C) \), of the BIC.

4. Concluding Remarks

The combustion experiments of a highly densified biomass fuel, Bio-coke (BIC), has been investigated to study its ignition characteristics in high temperature air flows, to evaluate its application to use in stoves or furnaces. The results obtained in this study may be summarized as follows;

(1) The experiments established the existence of two modes of ignition of the BIC. In the high temperature air (\( \geq 598 \) K), the solid surface ignition precedes the gas-phase ignition (Mode 1). On the other hand, the gas-phase ignition is observed simultaneously with the solid surface ignition in the low temperature air (\( \leq 573 \) K) (Mode 2).

(2) The solid surface ignition precedes the gas-phase ignition with high air flow rates (750 L/min.) even in the low temperature air (523 K).

(3) The solid surface ignition precedes the gas-phase ignition with the BIC which has...
low moisture content (dried-BIC) even in the low temperature air (573 K).

(4) It is suggested by numerical calculation that the thickness of the heated layer of the BIC (temperature distribution inside the BIC) depends on the heating rate at the beginning of heating. A thick heated layer of the BIC is formed in the low temperature air by taking a long heating time, whereas a thin heated layer is formed in the high temperature air with a quick heating. Since the region where the temperature exceeds the evolution temperature can release the evolved gas, the BIC which has a thick heated layer can release much evolved gas. Therefore, in the high temperature air, the evolved gas from the BIC at the beginning of heating is not sufficient to ignite the gas-phase, even when the surface temperature has increased high enough to ignite in the solid-phase. In the low temperature air, the surface ignition will occur later because of the low surface temperature and the BIC block has been heated longer and will ignite the gas-phase when enough evolved gas is available. The differences in the temperature distribution inside the BIC and the rates of change with time could be reasons why the BIC has two modes of ignition. It is suggested that the influence of heating rate on the surface temperature and the amount of gas evolution, which are closely correlated with the time-dependent temperature distribution inside the BIC, have to be taken into account in predicting the ignition process of the BIC due to its high density and resulting high heat capacity.

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References

[8] K.M.Bryden, M.J.Hagge, Modeling the combined impact of moisture and char


