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Numerical Modeling of a Deep, Fixed Bed Combustor

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A computational model to evaluate the anticipated performance characteristics of a deep, fixed bed combustor/gasifier utilizing whole trees as the source of fuel is presented. This combustor/gasifier is the heat source for a proposed steam-driven electric power plant utilizing whole trees as the source of fuel. In the simulation model presented, hardwood logs 20 cm in diameter are burned in a 3.7 m deep fuel bed. Solid and gas velocity and CO, CO_2, H_2O, hydrocarbon, and O_2 profiles are calculated. This deep bed combustor obtains high energy release rates per unit area due to the high inlet air velocity and extended reaction zone. The lowest portion of the overall bed is an oxidizing region and the remainder of the bed acts as a gasification and drying region. The overfire air region completes the combustion. Approximately 40% of the energy is released in the lower oxidizing region. The wood consumption rate obtained from the computational model is compared with test results obtained from full scale testing. The wood consumption rate predicted by the model is 2630 kg/(m^2 h) which matches well the consumption rate of 2670 kg/(m^2 h) observed during the 2 h test period of the field test. This corresponds to a heat release rate of 9.6 MW/m^2. The model is used to investigate the performance of the combustor under a variety of load conditions, fuel sizes, and moisture conditions.

Introduction

Biomass is an attractive fuel for electric power generation because it is a locally available, cost competitive, renewable energy source that reduces sulfur dioxide and has zero net carbon dioxide emissions when grown and utilized in a closed loop system. Increasingly in the future, the use of biomass as an energy resource will be driven by the need to reduce carbon dioxide emissions. In the energy production arena there are two significant areas for the large-scale use of biomass as a fuel—transportation and electric power generation. The most effective of these for offsetting carbon dioxide emissions is the use of plantation grown short-rotation woody crops in place of coal for electric power production.[1]

Among the technologies being investigated to meet this need for biomass power production is a steam power plant utilizing whole trees as the renewable fuel (Whole-Tree-Energy). This proposed electricity generating plant is being developed by Energy Performances Systems, Inc. of Minneapolis, MN.[2] In this system, hardwood trees, such as hybrid poplars, are grown on energy plantations and harvested as whole trees. These trees are transported to the power plant site and stored in a large covered stack. Waste heat from the power plant is used to dry the stored fuel. When dried to the desired moisture content, the whole trees are conveyed to the boiler and trimmed to 8 m in length (for a 100 MW plant). These tree segments are then added in batches to a deep fixed bed combustor/gasifier by means of a ram feeder located 6 m above a fixed grate. The fuel feed rate is set to maintain a fuel bed 3−4.5 m deep on a grate. Preheated air is blown upwards through the fuel bed such that the lower section of the bed has an oxidizing environment and the upper part of the fuel bed has a reducing environment. Combustion is completed by means of overbed air jets. This innovative system completed stacking, drying, and combustion tests at a site near Aurora, MN, in August 1992.[3] The advantages of this system are (1) time, energy, and processing costs are saved by not chipping the wood, (2) a 30 day supply of wood may be stored on site without degradation of the fuel, and (3) the combustion heat release per unit plan area is significantly greater than with wood chips. The concept is envisioned for 25 to 250 MW Rankine cycle power plants.

In this combustor tree sections are fed onto the top of a deep, fixed bed of reacting wood. A char layer is rapidly formed on the outside of the log. Pyrolysis products and moisture flow outward through the char layer cooling the surface and screening the surface from heat and mass transfer. Typically the oxygen flux will be zero in the upper part of the bed, and the char reacts with carbon dioxide and water vapor. The surface of the char is heated by the gaseous products and cooled by the reducing reactions of carbon dioxide and water vapor with the char. As the fuel moves downward in the bed, the char layer grows in thickness as the inner core of the undisturbed wood is pyrolyzed more rapidly than the outer char surface is consumed. In the lower portion of the bed, oxygen becomes available to react with the pyrolysis products. Near the bottom of the bed during the final 10% of the lifetime of the particle (tree section), the drying is completed and the entire particle is char and the char breaks into smaller pieces. The oxygen reacts directly with these char pieces, which are consumed rapidly, causing the entire bed to move downward. The ash is formed gradually as the char reacts and is blown upward; there is no ash bed in the grate.

⊗ Abstract published in *Advance ACS Abstracts*, February 15, 1996.
(1) Graham, R. L., et al. *Clim. Change* **1992**, *22*, 223−238.
(2) Lamarre, L. *EPRI J.* **1994**, *19*(1), 16−24.
(3) Schaller, B. J., et al. Report TR-101564 v. 2; EPRI, Palo Alto, CA, 1993.

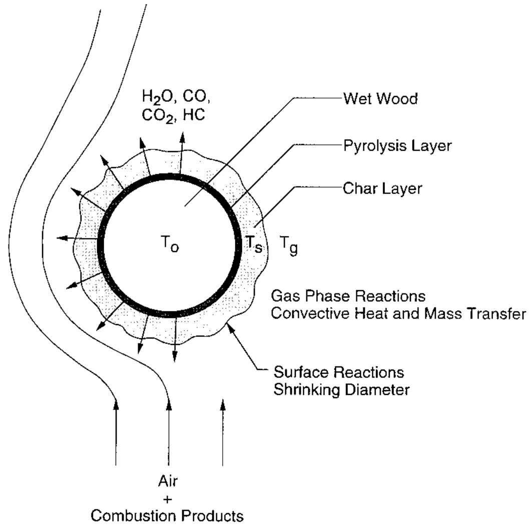

Figure 1. Reaction zones for thermally thick tree section during combustion.

The overall bed heat release rate depends on the heat and mass transfer to the logs; the formation of the char layer; the reaction rate of the char with oxygen, carbon dioxide, and water vapor; and the nature and rate of reaction of the pyrolysis products. The reaction rate of char with hydrogen is small and neglected.

As noted by Di Blasi,[4] both theoretical and experimental work provide a basis for the existence of two differing modes of wood combustion: thermally thin and thermally thick. In the case of smaller particles, such as sawdust or paper, combustion occurs as thermally thin combustion; the time scale of heat transfer within the particle is much shorter than the time scale of convective heat transfer to the particle. As a consequence, drying, pyrolysis, and char occur sequentially. In combustion of thermally thick fuel, the larger fuel size results in a thermal wave that drives the drying and the pyrolysis of the particle (Figure 1). Because of this the fuel consists of a relatively unchanged core surrounded by a char layer. These two regions are separated by a thin brown pyrolysis region. For the conditions encountered by a large wood particle (10 cm) in a furnace, Ragland et al.[5] measured the thickness of the pyrolysis region to be 1−3 mm with a strong dependence on particle moisture content. For large thermally thick materials tested under ASTM E 119 fire exposure conditions the thickness of the pyrolysis layer is approximately 5−10 mm.[6] Because of the larger particle size, drying, pyrolysis, and char combustion and gasification occur continuously throughout most of the life of the fuel particle.

Modeling of wood combustion is an active area of research with many different areas being actively pursued. Flame spread and ignition of both thermally thin and thermally thick charring materials have been investigated by several researchers. Jannsens[7] provides a detailed review of piloted ignition of wood and notes briefly the differing models for thermally thin and thermally thick materials. Di Blasi[4,8] discusses the mechanisms of flame spread for thick and thin materials. Pyrolysis of thermally thin and thermally thick material has been examined by numerous researchers. Antal and Varhegyi[9] provide an in depth review of cellulose pyrolysis kinetics. Similar to the situation noted by Brewster et al.[10] for coal combustion and gasification, limited data for large wood char particle combustion and gasification are available. Ragland et al.[5] report mass loss as a function of time for wood chunks up to 10 cm thick inserted in a spreader stoker fired with coal, and present a transient conduction model to account for the mass loss and growth of the char layer. Albini and Reinhardt[11] have examined the time to ignition and mass loss as a function of time for cylindrical wood elements with and without bark 2.5−10 cm in diameter under conditions representative of those experienced in a wildland fire.

Fixed bed combustion of wood has been modeled for wood chips (2 cm by 2 cm by 0.5 cm) in a deep (20−40 cm) pressurized downdraft combustor gasifier by Purnomo et al.[12] Key components of this model include high gas velocity, a thin char reaction zone (<1 cm), and resolution of the steep temperature gradients in the bed. Reed[13] et al. have modeled downdraft gasification of woody biomass up to 2.5 cm in diameter and 4 cm long, examining bed depth, particle size, and moisture content. Kayal et al.[14] modeled the gasification of bundled jute sticks in a continuous updraft gasifier. In this case the jute sticks (15 cm long and 1 cm o.d.) are tied into bundles with an average diameter of 74 mm. These bundles are placed in a reaction cylinder such that the jute sticks are parallel to the air flow vice in cross flow as might be expected. Of particular interest in this model is the very thin oxidation and reduction zone (~10 cm) in comparison with the overall reaction chamber height (1.5 m).

Although a limited number of numerical models of fixed bed wood combustion and gasification are available, numerous numerical models of fixed bed coal combustion and gasification have been reported. Brewster et al.[10] presents a detailed review of the current state of fixed bed coal combustion. These reviews have identified common features of fixed bed combustion and gasification computational modeling. Many of these features are included in this model. These include the following: (1) single initial particle size; (2) no momentum transport for gas and solid phase; (3) radially uniform gas and solid-phase flow; (4) axially and radially uniform bed void fraction; and (5) char or carbon combustion and gasification with kinetic analysis.

This article presents a computational model of a deep fixed bed of large thermally thick woody biomass segments approximately 20 cm in diameter. This model

(4) Di Basi, C. *Combust. Flame* **1994**, *97*, 225−239.
(5) Ragland, K. W., et al. *For. Prod. J.* **1988**, *38*(2), 27−32.
(6) *Wood Handbook: Wood as an Engineering Material*; Forest Products Laboratory; U.S. Dept. of Agriculture Handbook 72, 1987.
(7) Jannsens, M. *Fire Mater.* **1991**, *15*, 151−167.
(8) Di Blasi, C. *Combust. Flame* **1995**, *100*, 332−340.
(9) Antal, M. J.; Varhegyi, G. *Ind. Eng. Chem. Res.* **1995**, *34*, 703−717.
(10) Brewster, B. S., et al. In *Coal Science and Technology, vol. 20, Fundamentals of Coal Combustion for Clean and Efficient Use*; Smoot L. D., Ed.; Elsevier: New York, 1993; Chapter 8.
(11) Albini, F. A.; Reinhardt, E. D. *Int. J. Wildland Fires* **1995**, *5*(2), 81−91.
(12) Purnomo et al. *Symp. (Int.) Combust., [Proc], 23* **1990**, 1025−1032.
(13) Reed, T. B.; Markson, M. In *Progress in Biomass Conversion*; Tillman, D. A., Jahn, E. C., Eds.; Academic: New York, 1983; Vol. 4, pp 217−254.
(14) Kayal, T. K., et al. *Bioresour. Technol.* **1994**, *49*, 61−73.

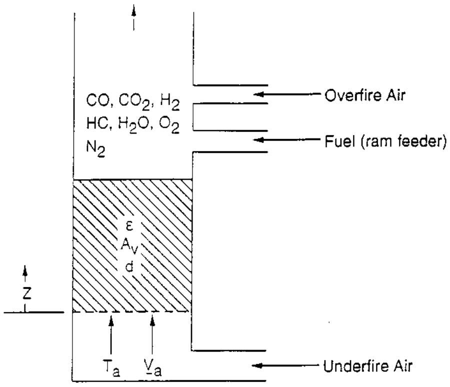

Figure 2. Schematic of deep bed combustor.

is then used to examine the expected behavior of the combustor to provide a basis for the design of the combustor. The areas investigated include the heat release per unit plan area and bed depth, and the impact of changing moisture content, fuel size, and underfire velocity. This model differs from the other fixed bed models due to the large, thermally thick biomass fuel. Additionally, the two-point boundary problem is reduced to an iterative process to find the particle diameter as a function of height. These aspects of the model are described in further detail in the text. Because the specific area of interest in this paper is the impact of fuel size and moisture content on the required bed depth, underfire air temperature, and velocity for a deep fixed bed with large woody biomass fuel, the overfire air region is not modeled.

Description of the Model

The model is a one-dimensional, steady state model for a top feed, updraft, fixed bed combustor (Figure 2). Heat loss to the walls surrounding the bed is neglected. An initial log diameter and a constant void fraction are used to characterize the pile, and the logs are assumed to be oriented across the gas flow. The surface area to volume ratio of the fuel is determined at each distance step in the bed as a function of diameter. As the log shrinks due to reaction with oxygen, carbon dioxide, and water vapor; moisture and wood volatiles are released from the wood. The model solves the equations of conservation of mass and energy for the solid, conservation of mass and energy for the gas, and conservation of gas phase species. Seven gas phase species are considered: oxygen, nitrogen, hydrogen, water vapor, carbon dioxide, carbon monoxide, and hydrocarbons. Hydrocarbons include all gaseous pyrolysis products except water, carbon dioxide, carbon monoxide, and hydrogen. Tars are included with the hydrocarbons. Hydrocarbons react with oxygen to form water and carbon dioxide. All gas phase physical properties including specific heat, diffusion coefficients, and density are functions of both species and temperature.

The gaseous species conservation equations in differential form are

$$\mathrm{d}(G_i)/\mathrm{d}z = r_i \qquad (1)$$

where G_i and r_i are the mass flux and chemical production/consumption rate per unit volume of species i, respectively, and z is the height of the combustor. The chemical production/consumption rate for each gaseous species is formed from the reactions shown in Table 1 and is as follows:

Table 1. Chemical Reactions Used in the Model

reaction no.	chemical reaction	heat of reaction (kJ/kg)
1	$2C + O_2 \rightarrow 2CO$	9 211
2	$2CO + O_2 \rightarrow 2CO_2$	10 107
3	$C + CO_2 \rightarrow 2CO$	−14 372
4	$C + H_2O \rightarrow H_2 + CO$	−14 609
5	$CH_{1.522}O_{0.028} + 0.867O_2 \rightarrow 0.761H_2O + CO$	17 473
6	$2H_2 + O_2 \rightarrow 2H_2O$	142 919

Table 2. Reaction Rate Equations

$\dot{\omega}_1 = \rho_{O_2} A_v (2M_C/M_{O_2}) h_{D1} k_1/(h_{D1} + k_1)$
$\dot{\omega}_2 = M_{CO_2} 10^{17.6} \exp(-2 \times 10^4/T_e)[CO][O_2]^{0.25}[H_2O]^{0.5}$ [a]
$\dot{\omega}_3 = \rho_{CO_2} A_v (M_C/M_{CO_2}) h_{D3} k_3/(h_{D3} + k_3)$
$\dot{\omega}_4 = \rho_{H_2O} A_v (M_C/M_{H_2O}) h_{D4} k_4/(h_{D4} + k_4)$
$\dot{\omega}_5 = M_{HC} 9.2 \times 10^6 T_e \exp(-(9650/T_e)[HC]^{0.5}[O_2]$ [a]
$\dot{\omega}_6$ is assumed to be instantaneous
where $h_{D_i} = D_i(2.0 + 1.1\mathrm{Re}^{0.6}\mathrm{Sc}^{1/3})\phi/d$ [b]
$\phi = 0.8$
$k_1 = 1.74 T_s \exp(-9 \times 10^3/T_s)$ [c]
$k_3 = 3.42 T_s \exp(-1.56 \times 10^4/T_s)$ [d]
$k_4 = 1.67 k_3$ [e]
$T_e = \alpha T_g + (1 - \alpha) T_s$ if $T_g \le T_s$ [f]
$T_e = T_g$ if $T_g > T_s$

[a] Smoot, L. D.; Smith, P. J. *Coal Combustion and Gasification*; Plenum Press: New York, 1985. [b] Wakao, N.; Kaguei, S. *Heat and Mass Transfer in Packed Beds*; Gordon and Breach: New York, 1982. [c] Evans, D. D.; Emmons, H. W. *Fire Res.* **1977**, *1*, 57−66. [d] Reference 10. [e] Yoon, H., et al. *AIChe J.* **1978**, *24*, 885−903. [f] Purnomo. Ph.D. Thesis, University of Wisconsin at Madison, Dec 1988.

Table 3. Mass Fraction Yield of Pyrolysis Products of Dry, Ash-Free Wood[a]

char	0.200
water	0.250
hydrocarbons[b]	0.247
carbon monoxide	0.183
carbon dioxide	0.115
hydrogen	0.050

[a] Ragland, K. W., et al. *Bioresour. Technol.* **1991**, *37*, 161−168. [b] $C_aH_bO_c$, $a = 1$, $b = 1.522$, $c = 0.0028$.

$$r_i = \sum_{j=1}^{N_r} b_{i,j}\dot{\omega}_j + y_i r_p \qquad (2)$$

where $b_{i,j}$ is the yield of species i in reaction j on a mass basis, $\dot{\omega}_j$ is the rate of reaction j and includes both chemical kinetics and diffusion (Table 2), and y_i is the mass fraction yield of species i due to the pyrolysis of wood (Table 3). Because of the thinness of the pyrolysis layer relative to the overall thickness of the wood, the pyrolysis and drying of the wood are assumed to occur in a negligibly thin area at the leading edge of the thermal wave, as shown in Figure 1. The heat of pyrolysis is assumed to be zero and the energy to dry the wood is included in the solid energy equation (eq 9). The rate of pyrolysis and drying of the wood is r_p. N_r is the number of reactions ($N_r = 6$). For example, the reaction rate of oxygen is

$$r_{O_2} = -\frac{1}{2}\frac{M_{O_2}}{M_C}\dot{\omega}_1 - \frac{1}{2}\frac{M_{O_2}}{M_{CO}}\dot{\omega}_2 - 0.867\frac{M_{O_2}}{M_{HC}}\dot{\omega}_5 - \frac{1}{2}\frac{M_{O_2}}{M_{H_2}}\dot{\omega}_6$$

The consumption rate of char is

$$r_{\mathrm{char}} = -\dot{\omega}_1 - \dot{\omega}_3 - \dot{\omega}_4 \qquad (3)$$

The pyrolysis rate of wood is

$$r_{\mathrm{p}} = r_{\mathrm{char}}\delta_{\mathrm{p}} \qquad (4)$$

where δ_p is the ratio of wood pyrolyzed and dried to char consumed. For wood, the ratio of wood pyrolyzed and dried to char consumed is initially high at the top of the bed as the wood is rapidly pyrolyzed and dried in the furnace environment and decreases as the diameter shrinks. The char combustion and gasification is assumed to be the rate-limiting step that sets the overall characteristics of the combustor.[5] When the char thickness reaches 2 cm, it is assumed that the fuel has been completely pyrolyzed. The ratio δ_p is based on analysis of the physical limits for the ratio and on data from the single log combustion tests performed in a specially designed furnace under conditions related to the WTE system.[15] In these tests it was found that the growth rate of the char at furnace level conditions could be described by a single equation for a wide range of large particle sizes, moisture contents, freestream gas compositions, and combustion rates. From this and the observation that the wood beneath the pyrolysis layer is essentially undisturbed, it was found that the ratio of wood pyrolyzed and dried to the rate of char consumed could adequately be modeled using

$$\delta_{\mathrm{p}} = C(r_{\mathrm{c}} - 2)^{1/2} \qquad (5)$$

where r_c is the radius of the remaining char and C is a constant chosen such that the char thickness is zero at the top of the bed. It should be noted that this relationship is only approximate and has been developed for large, 12−20 cm wood segments burning in cross flow at furnace level conditions in combustion gases. Additionally, the relationship works because although the in-bed temperature profiles and gas species profiles are altered, the overall energy release and mass consumption rate, which are the focus of this study, are not significantly affected by the form of the relationship. For example, if the pyrolysis and drying rate, δ_p, is assumed to be a linear function of the particle diameter, with the particle being completely char at 2 cm, which is a very rough approximation, the calculated mass consumption rate for the evaluation case described in the next section differs by less than 5% from that found using eq 5. The overall rate of consumption of the solid is $r_s = r_{\mathrm{char}} + r_p$.

The mass flux of the gas is

$$G_{\mathrm{g}} = \sum_{i=1}^{N_{\mathrm{s}}} G_i \qquad (6)$$

where N_s is the number species. The solid velocity is determined from

$$(1-\epsilon)\rho_{\mathrm{c}}\frac{\mathrm{d}V_{\mathrm{s}}}{\mathrm{d}z} = r_{\mathrm{c}} \qquad (7)$$

where ϵ is the void fraction of the bed, ρ_c is the density of the char, and V_s is the downward solid velocity. Conservation of energy for the gas is

$$\frac{\mathrm{d}(G_{\mathrm{g}}h_{\mathrm{g}})}{\mathrm{d}z} = \sum_{j=1}^{N_{\mathrm{r}}}\Delta H_j\dot{\omega}_j - y_{\mathrm{H_2O}}r_{\mathrm{p}}h_{\mathrm{fg}} \qquad (8)$$

where h_g is the enthalpy of the mixture and ΔH_j is the heat of reaction for reaction j. Conservation of energy for the solid is based on a surface energy balance,

$$A_{\mathrm{v}}h_{\mathrm{conv}}(T_{\mathrm{s}} - T_{\mathrm{g}}) = \Delta H_1\dot{\omega}_1 + \Delta H_3\dot{\omega}_3 + \Delta H_4\dot{\omega}_4 + \dot{m}_{\mathrm{r}}h_{\mathrm{r}} - \dot{m}_{\mathrm{p}}h_{\mathrm{p}} \qquad (9)$$

where h_{conv} is the convective heat transfer coefficient, A_v is the char surface area per unit bed volume, h_r is the enthalpy of the reactants, and h_p is the enthalpy of the products including pyrolysis products. The change in the sensible enthalpy of the char is neglected. The convective heat transfer coefficient is obtained from a correlation for nonreacting fixed beds with a screening factor to account for mass transfer (Table 2).

The boundary conditions for the inlet air velocity, temperature, and the gas composition are specified at the grate ($z = 0$). The solid velocity of the fuel at the grate is zero. Log size and as-received moisture content are specified at the top of the bed. Equations 1−9 are solved by using a stiff ordinary differential equation solver starting at the bottom of the bed and marching up the bed. By use of eq 5 the correct moisture content and fuel density is obtained at the top of the bed. To obtain the heat and mass transfer coefficients at each step of the integration, the diameter of the fuel must be known. However, the diameter is known only at the top and bottom of the bed. To solve this problem, an assumed fuel diameter as a function of height is used and the equations are solved for the entire bed height. The resulting solid velocity as a function of height is then used to update the assumed fuel diameter using the relationship

$$\frac{V_{\mathrm{s}}|_{\mathrm{top}}}{{d_{\mathrm{top}}}^2} = \frac{V_{\mathrm{s}}|_z}{{d_z}^2} \qquad (10)$$

which is valid at all heights within the combustor up to the point of char breakup. This iteration is continued until the fuel diameter as a function of height converges, generally three to six iterations. Because no data are available for the breakup of the char under these conditions, a linear relationship between the bed depth and the char diameter is assumed in the char breakup region. This is an area that requires further research and study as small changes in this assumed distribution will alter significantly the output of the model. Because the same assumption is used for all cases it is anticipated that the impact of fuel size, moisture content, and bed depth can be accurately predicted.

Evaluation of the WTE Combustor/Gasifier Model

Combustion tests were run at Aurora, MN in August 1992 using a 1.4 m by 2.6 m by 3.7 m deep bed of hardwood logs with an average size of 20 cm, an average as-received moisture content of 31.6%, and an average

(15) Bryden, K. M.; Ragland, K. W. Submitted for publication in *Developments in Thermochemical Biomass Conversion*.

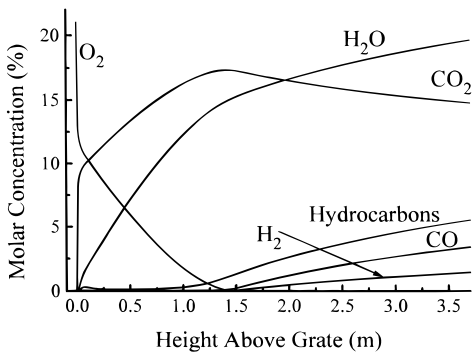

Figure 3. Gas species concentration vs height above grate. Inlet air preheat of 400 °C, fuel moisture content of 23%, underfire inlet air velocity of 3.7 m/s, fuel size of 20 cm, and bed height of 3.7 m.

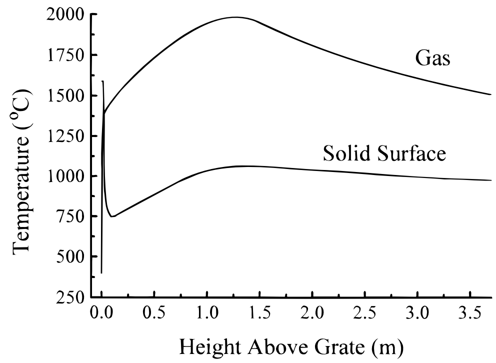

Figure 4. Solid surface and gas temperature vs height above grate. Inlet air preheat of 400 °C, fuel moisture content of 23%, underfire inlet air velocity of 3.7 m/s, fuel size of 20 cm, and bed height of 3.7 m/s.

void fraction of 0.65. The fuel was supported by cooled steel tubes 6.4 cm diameter on 22 cm centers. The underfire air was preheated to approximately 275 °C and the average air flow rate was 565 kg/min, which gave an inlet velocity under the bed of 3.8−4.1 m/s. The average wood burning rate during the 2 h test was 162 kg/min, and the average burning rate per plan area was 2670 kg/(m^2 h). The heat release rate per unit plan area was 10.1 MW/m^2, and the peak was 12.9 MW/m^2.[3] These heat release rates are high compared to a coal-fired spreader−stoker because of the deep fuel bed and the high inlet air velocity.

The simulation model was run for the above conditions assuming a representative fuel size of 20 cm, a bed void fraction of 0.65, inlet air temperature of 275 °C, and an inlet air velocity of 3.95 m/s. The lowest portion of the fuel bed consists of small diameter char where the oxygen is rapidly consumed and the temperature rises rapidly. Above the oxidizing region is an extended reducing region where the logs are slowly dried and pyrolyzed and the char layer reacts with carbon dioxide and water vapor. The predicted burning rate per unit area for these conditions and assumptions is 2630 kg/(m^2 h), which compares well with the measured burning rate of 2670 kg/(m^2 h). Assuming a higher heating value of 19.1 MJ/kg for dried wood, the corresponding heat release rate is 9.6 MW/m^2.

Simulated Performance of the WTE Combustor/Gasifier

The proposed design conditions for the combustor/gasifier for a 100 MWe WTE power plant specify a 4.3 m by 8.5 m by 3.7 m deep fuel bed of hardwood logs with an average initial size of 20 cm diameter with 23% as-received moisture, an inlet air velocity of 3.2 m/s, and 400 °C inlet air temperature. Keeping all the other model parameters the same as in the evaluation run above, the predicted heat release rate is 8.6 MW/m^2. Overfire air is needed to complete combustion, and the predicted overfire air to underfire air ratio is 0.67. The predicted gaseous species profiles in the fuel bed for the design case with an inlet air velocity of 3.2 m/s are shown in Figure 3. The first 35% of the bed (∼1.4 m) is an oxidizing region in which the oxygen is completely consumed. The upper 65% of the bed is a reducing region in which the char−carbon dioxide and char−water vapor reactions dominate. The hydrocarbons, carbon monoxide, and hydrogen that are formed in the reducing region are burnt out in the overfire air region. The fuel is pyrolyzed in the upper 98% of the bed and pure char exists only in the lowest 2% of the bed. The predicted gas and solid surface temperatures are shown in Figure 4. The solid surface temperature just above the grate is high because the high oxygen concentration is reacting with relatively small particles of pure char. As the char surface reaction decreases and as the volatiles and moisture escape through the surface of the fuel, the surface temperature is reduced rapidly. Further above the grate, the surface temperature rises due to heat transfer from the gaseous combustion products. At about 1.4 m above the grate the oxygen is consumed and the char reducing reactions gradually decrease the temperatures. The gas velocity at the top of the bed, prior to the overfire air, is 12.1 m/s when the inlet air is 3.2 m/s.

Several different options are available to the designer and operator to meet the goal of producing a given heat release rate to meet a given load. The underfire inlet air velocity may be changed by changing the air flow rate. The underfire air temperature may be changed by adjusting the air preheat. The fuel bed height may be increased or decreased by adjusting the fuel feed rate, and the fuel moisture content may be changed by adjusting the drying time. The impact of these is as follows:

1. Increasing the underfire air velocity while adjusting the fuel feed rate to maintain a constant bed height results in a higher burning rate as the oxygen penetrates further into the bed. This consumes char at a greater rate, increasing the overall temperature of the bed, which increases the rate of heat transfer to the fuel. This in turn increases the drying and pyrolysis rate of the fuel. For a given bed height, the increase in the heat release rate that can be achieved by increasing the underfire air flow rate is limited by the maximum pressure drop across the bed, carryover of partially burned fuel particles, and possible tube erosion.

2. Increasing the fuel feed rate while maintaining the underfire air flow rate, air temperature, fuel moisture, and fuel size constant increases the bed height, which lengthens the gasification zone and also increases the heat release rate. This requires the overfire air to be increased. The predicted combined effect of increasing the inlet air flow and the bed height on the heat release rate is shown in Figure 5.

3. Increasing the underfire air preheat temperature

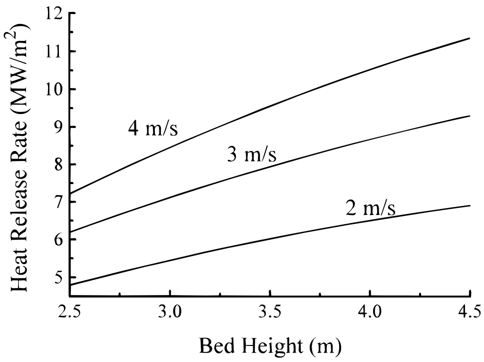

Figure 5. Heat release rate vs bed height and underfire air velocity. Inlet air preheat of 400 °C, fuel size of 20 cm, and fuel moisture content of 23%.

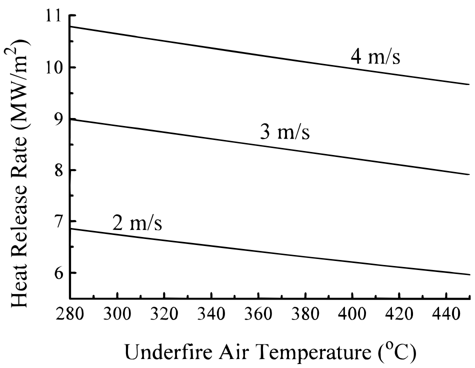

Figure 6. Heat release rate vs underfire air temperature and underfire air velocity. Bed height of 3.7 m, fuel size of 20 cm, and fuel moisture of 23%.

while maintaining the underfire air flow rate and adjusting the fuel feed rate to maintain the bed height constant decreases the heat release rate (Figure 6). The deep, fixed bed combustor act as a combustor/gasifier in which the combustion of char and pyrolysis products in the lower portion of the bed provides the energy to support the drying, pyrolysis, and gasification in the upper portion of the bed. As the temperature of the underfire air increases, the density of the air is lowered. This reduces the mass flux rate of the oxygen delivered to the fuel bed. The reduced oxygen flux results in a lower heat release rate in the lower portion of the bed. This lower heat release in the lower portion of the bed results in a lower drying, pyrolysis, and gasification rate.

4. Increasing the fuel moisture content while maintaining all other parameters constant decreases the heat release rate (Figure 7). This occurs because the increased moisture levels increase the drying time and decrease the convective heat transfer to the particle by increasing the blowing rate at the surface of the particle.

5. As the fuel size increases, the length of time to dry and pyrolyze the fuel and consume the char increases. On the basis of this, if the fuel size is increased and the fuel feed rate is adjusted to maintain a constant bed height and all other parameters are held constant, the heat release decreases as shown in Figure 8.

6. The theoretical air (actual underfire/stoichiometric air flow rate) as a function of bed height and underfire inlet air velocity is shown in Figure 9. As the bed height is increased, more fuel is gasified, but a limit is reached because the gas temperature drops too low to support a substantial pyrolysis and gasification reaction rate.

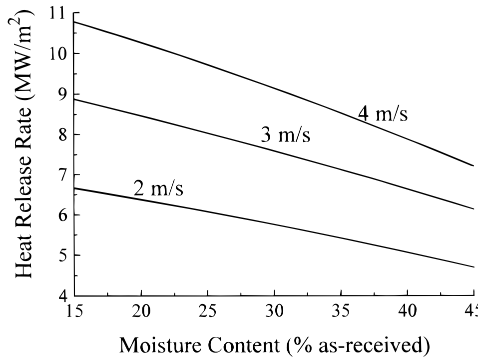

Figure 7. Heat release rate vs fuel moisture content and underfire air velocity. Inlet air preheat of 400 °C, fuel size of 20 cm, and bed height of 3.7 m.

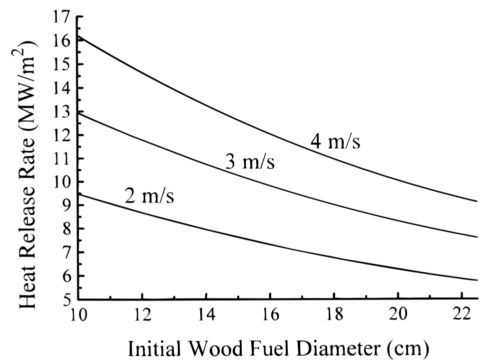

Figure 8. Heat release rate vs fuel size and underfire air velocity. Fuel size of 20 cm, inlet air preheat of 400 °C, bed height of 3.7 m, and fuel moisture content of 23%.

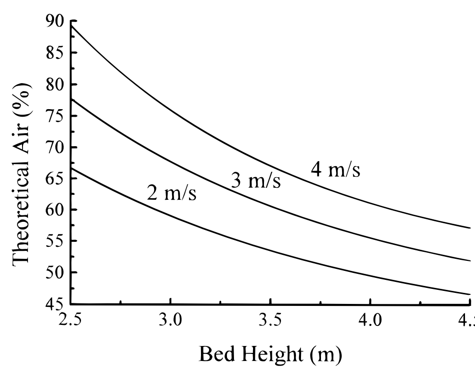

Figure 9. Percent theoretical air vs bed height and underfire air velocity. Inlet air preheat of 400 °C and fuel moisture content of 23%.

From this discussion it is obvious that there is a relatively broad range of combinations of bed height, underfire air temperature, and underfire air velocity that can be used to obtain a desired heat release rate. For example, with a fuel moisture content of 23% as-received, and a fuel size of 20 cm, and a constant inlet air preheat temperature of 400 °C, a combustor designed to accommodate a maximum bed height of 3−4 m with inlet air velocities ranging from 2 to 4 m/s would have heat release rates from 5.5 to 10.5 MW/m^2. Bed height, underfire air flow rate, and underfire air temperature provide a “box” in which the designer can vary each of the parameters and still obtain the desired heat output. This flexibility is of significant importance in the design and planned operation of a first of a kind power unit. This flexibility permits a wider range of fuel moisture content and sizes to be used for the fuel. Additionally, if during initial operation it is found that one parameter (e.g., fuel size or moisture content) must be altered from the designed value, other parameters can be adjusted to maintain the desired power output.

Conclusions

A computational model for a deep fixed bed combustor utilizing thermally thick woody biomass fuel has been developed and evaluated with field test results. The combustor obtains high energy release rates due to the high air velocity and extended reaction zone. Additionally, the model has been used to investigate the operating characteristics of the combustor. The lowest portion of the bed is an oxidizing region and the remainder of the bed acts as a gasification and drying zone. For the 100 MW design case with 23% fuel moisture, inlet air preheat of 400 °C, and underfire air inlet velocity of 3.2 m/s, the predicted heat output per unit bed area is 8.6 MW/m^2, which is significantly higher than coal-fired spreader–stokers. The fundamental operating characteristics of this type of combustor provide a broad range of options for bed height, underfire air flow rate, and underfire air preheat temperature to obtain a desired heat release rate. This flexibility in operating conditions is a significant aid in the design and startup of this unique type of biomass power source.

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Glossary

A_v	surface area per unit volume, m^{-1}
$b_{i,j}$	yield of species *i* from reaction *j* on a mass basis, kg/kg
d	diameter, m
D	diffusivity, m^2/s
G	mass flux, kg/(m^2 s)
h_{conv}	heat transfer coefficient, W/(m^2 K)
h_D	mass transfer coefficient, m/s
h_{fg}	latent heat of vaporization, kJ/kg
h	enthalpy per unit mass, kJ/kg
ΔH	heat of reaction, kJ/kg
k	reaction rate constant, m/s
M	molecular weight, kg/kmol
N_r	number of reactions
R	universal gas constant, cm^3 atm/(kmol K)
Re	Reynolds number
r	net production (consumption) rate per unit volume, kg/(m^3 s)
Sc	Schmidt number
t	time, s
T	absolute temperature, K
V_s	solid velocity, m/s
y_i	mass fraction yield of pyrolysis products
z	height, m
α	weighting factor
ϵ	void fraction
δ_p	ratio of wood dried and pyrolyzed to char consumed
ρ	density, kg/m^3
ϕ	screening factor
ω	reaction rate per unit volume, kg/(m^3 s)

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