

NUMERICAL MODELING OF A DEEP, FIXED BED COMBUSTOR

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INTRODUCTION

A steam power plant utilizing whole trees as the renewable fuel (Whole-Tree-Energy™) is being developed by Energy Performances Systems, Inc. of Minneapolis, MN [1]. Hardwood trees are grown and harvested on energy plantations, or harvested from inferior, over-aged standing trees, transported in trucks as whole trees, and stored in a large covered stack at the power plant site where the stack is dried with waste heat from the power plant. When dried to the desired moisture content, the whole trees are burned in a fixed bed boiler. This innovative system completed stacking, drying and combustion tests at a site near Aurora, MN in August, 1992 [2].

The advantages of the proposed 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 greater than with wood chips. The concept is envisioned for 25 MW to 400 MW Rankine cycle power plants.

In the WTE combustor a ram feeder located 6 m above a fixed grate injects batches of trees trimmed to 8 m in length (for a 100 MW plant) with trunks up to 20 cm in diameter. The fuel feed rate is set to maintain a fuel bed 3 to 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.

Tree sections are fed onto the top of a deep, fixed bed of reacting wood. These sections are dried further and pyrolyzed forming a char layer on the outside of the log. Pyrolysis products and moisture flow outward through the char layer. Typically the oxygen flux will be zero in the upper part of the bed, and the char will react with the carbon dioxide and water vapor. The surface of the char will be 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 will grow 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. When the log is completely dried and pyrolyzed in the lowest portion of the bed the oxygen reacts directly with the char and the char is consumed rapidly, causing the entire bed to move downward. 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.

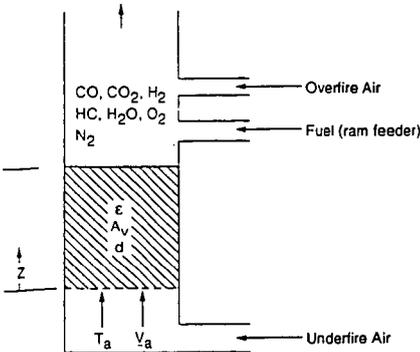


Fig. 1. Schematic of deep bed combustor.

DESCRIPTION OF THE MODEL

The model is a one-dimensional, steady state model for a top feed, updraft, packed bed combustor (Fig 1). It is assumed that the walls are adiabatic. The char reaction is assumed to be the rate limiting step and sets the pyrolysis rate [4]. 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

Table 1. Chemical Reactions Used in the Model.

Reaction #	Chemical Reaction	Heat of Reaction (kJ/kg)
1	$2 C + O_2 \rightarrow 2 CO$	9,211
2	$2 CO + O_2 \rightarrow 2 CO_2$	10,107
3	$C + CO_2 \rightarrow 2 CO$	-14,372
4	$C + H_2O \rightarrow H_2 + CO$	-14,609
5	$CH_{0.152}O_{0.028} + 0.867 O_2 \rightarrow 0.761 H_2O + CO$	17,473
6	$2 H_2 + O_2 \rightarrow 2 H_2O$	142,919

from the wood. For dry wood the ratio of wood consumed to char consumed is initially high at the top of the bed as the wood is rapidly pyrolyzed in the furnace environment and decreases as the diameter shrinks. When a 3 cm diameter is reached, the fuel remaining is assumed to be all char. The ratio is set based on data from the single log combustion tests performed in a specially designed furnace under conditions related to the WTE system [3]. 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 nitrogen.

The gaseous species conservation equations in differential form are,

$$\frac{d(G_i)}{dz} = r_i \quad [1]$$

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

$$r_i = \sum_{j=1}^{N_r} b_{i,j} \dot{w}_j + y_i r_{wood} \quad [2]$$

where $b_{i,j}$ is the stoichiometric yield of species i in reaction j on a mass basis, \dot{w}_j is the rate of reaction j , y_i is the mass fraction yield of species i due to the pyrolysis of wood (Table 2), and N_r is the number of reactions ($N_r = 6$). The reaction rates include both chemical kinetics and diffusion. The consumption rate of char is

$$r_{char} = h_{char,1} \dot{w}_1 + h_{char,3} \dot{w}_3 + h_{char,4} \dot{w}_4 \quad [3]$$

The reaction rate of wood is

$$r_{wood} = r_{char} K_{wood} \quad [4]$$

where K_{wood} is the ratio of wood consumed to char consumed.

The mass flux of the gas is

$$G_g = \sum_{i=1}^{N_s} G_i \quad [5]$$

where N_s is the number species. Conservation of mass for the solid is

$$(1 - \epsilon) \rho_s \frac{dV_s}{dz} = r_s \quad [6]$$

where ϵ is the void fraction of the bed, ρ_s is the density of the solid, r_s is the net reaction rate per unit volume of the solid, and V_s is the downward solid velocity.

Conservation of energy for the gas is,

$$\frac{d(G_g h_g)}{dz} = \sum_{j=1}^{N_r} \Delta H_j \dot{w}_j - y_{H_2O} r_{wood} \quad (7)$$

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,

$$A_s h_{conv} (T_s - T_g) = \Delta H_1 \dot{w}_1 + \Delta H_3 \dot{w}_3 + \Delta H_4 \dot{w}_4 + \dot{m}_r h_r - \dot{m}_p h_p \quad [8]$$

where h_{conv} is the convective heat transfer coefficient, A_s 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 convective heat transfer coefficient is obtained from a correlation for non-reacting beds [5] with a screening factor to account for mass transfer [6].

Table 2. Mass Fraction Yield of pyrolysis products of dry, ash free wood [7].

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

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. Eqs. 1 through 8 are solved by using a differential-algebraic implicit solver.

VALIDATION 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 top size of 20 cm and an average as-received moisture content of 31.6%. 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 m/s to 4.1 m/s. The average wood burning rate during the 2 hr test was 162 kg/min, and the average burning rate per plan area was 2670 kg/hr-m². The heat release rate per unit plan area was 10.1 MW/m², and the peak was 12.9 MW/m². 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

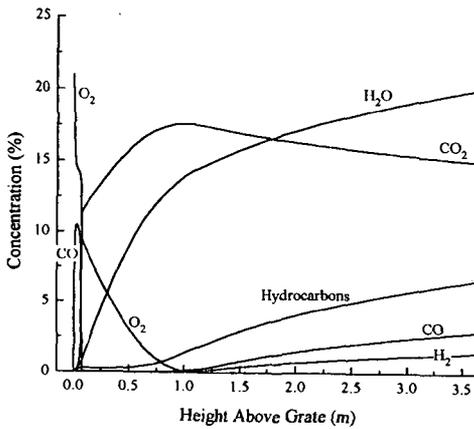


Fig. 2. Gas species concentration vs. height above grate. Inlet air preheat of 400°C, fuel moisture content of 23%, underfire inlet air velocity of 3.7 m/s, and bed height of 3.7 m.

17.8 cm, a bed void fraction of 0.60, inlet air temperature of 260°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 slowly are 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 2960 kg/hr-m², which compares well with the measured burning rate of 2670 kg/hr-m². Assuming a higher heating value of 19.1 MJ/kg for dried wood, the corresponding heat release rate is 10.7 MW/m², which is within 6% of the Aurora test.

SIMULATED PERFORMANCE OF THE WTE COMBUSTOR/GASIFIER

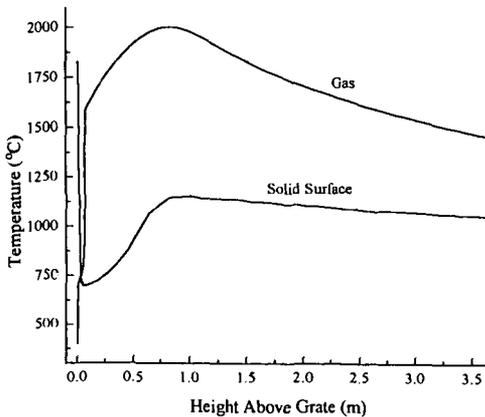


Fig. 3. Solid surface and gas temperature vs. height above grate. Inlet air preheat of 400°C, fuel moisture content of 23%, underfire inlet air velocity of 3.7 m/s, and bed height of 3.7 m/s.

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 top size of 20 cm diameter with 23% as-received moisture, and 400°C inlet air temperature. Keeping all the other model parameters the same as the validation run above, the predicted heat release rate is 9.5 MW/m² with an inlet air velocity of 3.2 m/s. Overfire air is needed to complete combustion, and the predicted overfire air to underfire air ratio is 0.85. The predicted gaseous species profiles in the fuel bed for the design case with an inlet air velocity of 3.7 m/s are shown in Fig. 2. The first 25% of

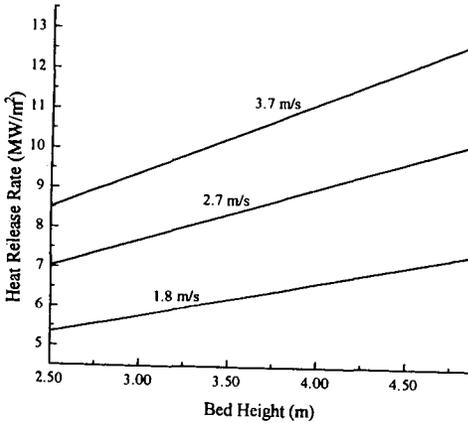


Fig. 4. Heat release rate vs. bed height and underfire air velocity. Inlet air preheat of 400°C and fuel moisture content of 23%.

fuel, the surface temperature is reduced rapidly, but then rises further above the grate due to heat transfer from the gaseous combustion products. At about 1 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 12.5 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 causes a higher burning rate as the oxygen penetrates further into the bed. This consumes more char increasing the overall temperature, increasing the heat transfer to the fuel. This in turn increases the drying and pyrolysis of the fuel. However, excessive air velocity will cause higher pressure drop across the bed, more carry-over of partially burned fuel particles, and possible tube erosion. The predicted combined effect of increasing the inlet air flow and the bed height on the heat release rate is shown in Fig. 4.
2. Increasing the bed height lengthens the gasification zone and also increases the heat release rate, provided more overfire air is used.
3. Increasing the underfire air preheat decreases the fuel burning rate for a fixed underfire

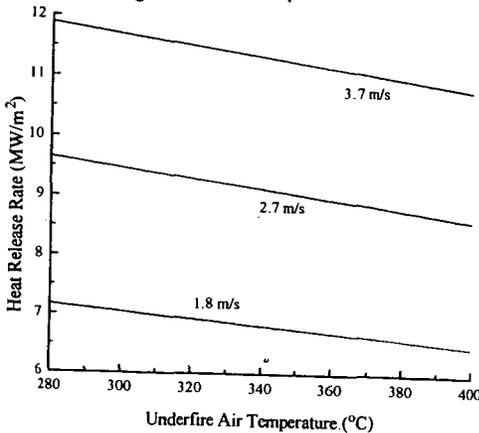


Fig. 5. Heat release rate vs. underfire air temperature and underfire air velocity. Bed height of 3.7 m and fuel moisture of 23%.

the bed (~1 m) is an oxidizing region in which the oxygen is completely consumed. The upper 75% 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 reducing region, are burnt out in the overfire air region. The fuel is pyrolyzing 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 Fig. 3. The solid surface temperature just above the grate is high because the high oxygen concentration is reacting with pure char. As the char surface reaction decreases and as the volatiles and moisture escape through the surface of the

air velocity, because less air mass flow is delivered to the fuel bed (Fig. 5). Although the chemical reaction rates tend to be increased by increased temperature, the reactions in the bed are more limited by mass transfer than kinetics.

4. Increasing the fuel moisture content decreases the pyrolysis rate because the temperatures are lowered, thus lowering the heat release rate, all else remaining constant (Fig. 6).

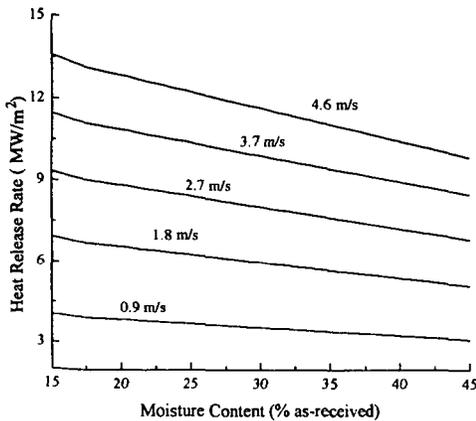


Fig. 6. Heat release rate vs. fuel moisture content and underfire air velocity. Inlet air preheat of 400°C and bed height of 3.7 m.

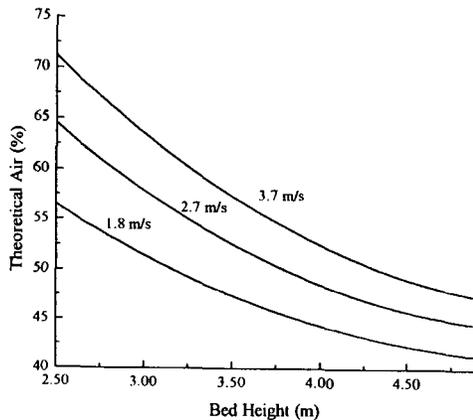


Fig. 7. % theoretical air vs. bed height and underfire air velocity. Inlet air preheat of 400°C and fuel moisture content of 23%.

The theoretical air required for complete combustion varies primarily with bed height and underfire inlet air velocity (Fig. 7). As the bed height is increased, more fuel is gasified, but a limit is reached because the gas temperature drops too low to support the reduction reactions and the carbon dioxide is consumed.

CONCLUSIONS

A computational model for the WTE combustor has been developed and adjusted to within 6% of heat output of 10.1 MW/m² of the Aurora, MN test run. The deep, fixed bed combustor obtains high energy release rates due to the high air velocity and extended reaction zone. 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 9.5 MW/m². The heat output of the combustor/gasifier can be changed by altering the underfire air flow rate, the bed height, the air preheat, and the fuel moisture.

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