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A QUASI-STEADY STATE SHRINKING CORE MODEL OF "WHOLE TREE" COMBUSTION IN A COUNTERCURRENT FIXED-BED

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Résumé : Modèle quasi-stationnaire de combustion de bois «brute» dans un générateur à lit fixe et à contre-courant

Un modèle de combustion de bois "brute" dans un lit fixe et à une dimension est développé et les résultats sont comparés à ceux de modèles ou de prototypes déjà existants Pour les besoins de la formulation, on suppose que chaque combustible est contenu dans une sorte d'enveloppe fictive en forme de tube carré de côté L et de longueur égale à celle du générateur. Les combustibles sont introduits de manière uniforme par le haut du générateur en rangés de N combustibles à une fréquence de V* rangés/s se déplaçant à contre-courant des gaz préchauffés qui ont une vitesse superficielle Vs. Les Combustibles migrent ensuite vers le bas du lit à une vitesse Vf. Malgré sa simplicité, le modèle permet de déterminer avec une assez bonne précision le temps de combustion et la profondeur du lit du foyer d'une Centrale Thermique de 100 MW de puissance brûlant du bois de 10 cm de rayon à une teneur en eau de 33.3%

Mots clés : Biomasse, bois, combustion, lit fixe

Nomenclature

A	external surface area (m^2)
b_c	char thickness (m)
C	oxygen concentration (kg/m^3)
C_{pj}	specific heat of component j (kJ/kg°K)
D	molecular diffusivity (m^2/s)

h	heat transfer coefficient (kJ/m^2-s-°K)
h_D	mass transfer coefficient (m/s)
hfg_m	specific enthalpy of phase change of liquid water (kJ/kg)
hfg_v	specific enthalpy of phase change of active matter(kJ/kg)
Hag	average specific heat of combustion of gas inside the bed (kJ/kg)
Hj	specific enthalpy of component j (kJ/kg)
K	geometry correction factor
K_c	char conductivity (kW/m-°K)
mc	moisture content (%)
r_0	initial radius (also Ro) (m)
r	shrinking radius (m)
T	temperature (°C)
W	width of the bed
z	bed coordinate (m)
l	lenght of «whole tree» and bed (m)
ρ	density (kg/m^3)
H	high of bed (m)

Dimensionless variables

Re_D	Reynolds number
S_g	Specific gravity

Subscripts

b	bulk
g	gas
i	initial (ambient), stoichiometric index = 12/16
j	components (c, m, v)
w	virgin wood
∞	free stream

INTRODUCTION

In recent years, a new approach in utilizing wood resources has been proposed [1] wherein "Whole tree" (without pre-processing operations such as chipping, etc.) are burned directly as a bed in a stoker boiler to produce electricity by steam turbine conversion. "Whole tree" burn, however, is more than just a novel combustion concept as it also includes improvement in such operations as fuel resource utilization, fuel drying, fuel handling, and heat recovery. It emphasizes hardwood tree species that are not acceptable to the pulp and paper industry and, therefore, not to most chip suppliers. This biomass resource may come from natural forests or be grown from select species. Potentially, such units could be capable of operating less expensively if fuel throughput, air flow and other variables can be optimized.

Figure 1 shows the sequence of operations in a "Whole tree" plant. Some of the advantages of the "Whole tree" combustion provided by the early feasibility assesssment and technologies comparison made by the Research Triangle Institute (RTI) [2] are :

- minimized fuel preparation and handling
- combined fuel drying and storage
- allow for deep-bed combustion (potentially efficient countercurrent flow and high heat release rate)

The primary disadvantages are the uncertainties in terms of interaction of various components and in terms of large-scale operation. Boiler technology is reasonably well established for woodchips and pulverized-coal firing. Additional modifications are required, however, for the design of "Whole tree" fired boilers and most investigations focus on the boiler efficiency (steam enthalpy produced per fuel heating value imput) and heat release rate.

The objective of the present work is then to provide reliable basic data on "Whole tree" residence time as a function of fuel elements properties (size, moisture content) and gas flow characteristics, for the design of wood fired boilers. The work is divided in two main parts. First, a one-dimensional "Whole tree" fixed bed combustion model is developed based on a shrinking core burning rate submodel and second, the results of the model whenever possible are compared with those of existing "Whole tree" combustion facilities or models.

MODEL DEVELOPMENT

An under-fired "Whole tree" fixed-bed, figure 3, is loaded uniformly from the top in rows of N fuel elements at a frequency of V* rows/sec which corresponds to a total fuel rate of 56.50 ton/hr (dry basis). This fuel bed rests on a water-cooled fixed grate and is designed to fire a 100 MW "Whole tree" power plant. For computational purposes, dimensions and characteristics, are assumed to be those of an actual unit described by the Research Triangle Institute (RTI) [2], Figure 2. The fuel elements are then subjected to an upward flow of preheated air stream at a theoretical requirement of 6.31 Kg of air per kg of dry wood with a superficial velocity Vs at a constant pressure of 1 atm. The "Whole tree" elements migrate through the bed with a velocity V_f while their initial radius r_0 shrinks to rf at the fixed grate. The distance traveled defines both the residence time and the depth of the combustion zone which are function of fuel properties and gas flow characteristics. The bed is assumed to be one-dimensional, steady state, while quasi-steady state conditions are assumed within the fuel elements. The partial drying of the fuel elements, which takes place over the outside layers and occurs during the transient warming period is neglected compared to the burnout time. The boiler startup, assumed to be acomplished in a 4 hr time is not modeled.

1. Burning rate submodel

It has been shown in reference [3] that the best formulation for the combustion of large wood specimens is the shringing core model, where it is understood that burnout is not accomplished until the combustion front reaches the center of the fuel elements. As a matter of fact, the rate of combustion is basically heat and diffusion controlled rather than reaction kinetics controlled.

In their investigations, the RTI found that most theoretical derivations and experience tests of fuel burnout have been conducted for wood particles not larger than 1 to 2 cm in size. There are few exceptions such as chunkwood tests (up to 10 cm in diameter) and even in this case results have to be extrapolated to larger wood and higher moisture content for comparison with whole tree burn process. The present model has been developed in an attempt to fill in this gap.

The mass loss rate by the shrinking core formulation applied to chunkwood has been extensively studied by reference [3] and submitted to publication [4]. For whole tree regarded as long cylinders, it reduces to

$$\frac{dm}{dt} = (2\pi r \ell)\left[\rho_c \frac{dr}{dt} + (\rho_w - \rho_c)\left(1 - \frac{bc}{r}\right)\frac{dr_w}{dt}\right] \qquad (1)$$

where $\frac{dr}{dt} = -\left(\frac{12}{16}\right) h_D C_\infty / \rho_c$; $\rho_w = S_g(1 + mc)\rho_{water}$ [5]

$r_w = r - b_c$

h_D is the overall mass transfer coefficient i.e the oxygen mass transfer coefficient modified by blowing and correlated in the same study [3,4] from the combustion of a single chunkwood element. For the bed, the actuel mass transfer coefficient is modified from that of a single chunkwood element by the introduction of the bed solid fraction ε_b, that is

$$\frac{.766mc\ r_o/r}{e^{(.533mc\ r_o/r)}-1}$$

$$h_D = \frac{2.06KDRe_D^{.425}}{\varepsilon_b(2r)}$$

The solution of equation (1) requires an explicit relation for the char layer thickness bc.

2 - *THE MIGRATION VELOCITY SUBMODEL*

Keeping with the assumption of quasi-steady state conditions in each whole tree element, we now shift from a material time-rate derivation to a one dimensional spatial-rate, i.e

$$V = \frac{dz}{dt}$$

$$\frac{dm}{dt} = V_f \frac{dm}{dz} \quad \text{where} \quad ; \text{ Similary} \quad \frac{dr}{dt} = V_f \frac{dr}{dz}$$

where V_f is the migration velocity of the whole tree. To model V_f, we will refer to figure 3 where a fuel cell and a sketch of the fuel bed are showned. We assume that the spreader stoker spreads fuel rods uniformly in N fuel rods per row at a frequency of V* rows/s.The bed void fraction ε_s is defined as

$$\varepsilon_s = \frac{L^2\ell - \pi\, r^2\ell}{L^2\ell} \text{ ; where } = 1 - \pi\left(\frac{r}{L}\right)^2$$

The characteristic lenght L of the fuel cell is then given by

$$L = \left(\pi/\varepsilon_b\right)^{1/2} r \qquad \varepsilon_b = 1 - \varepsilon_s$$

Now, the number of fuel rods per row N can be computed as

$$N = \frac{W}{L} = \frac{W}{r}\left(\frac{\varepsilon_b}{\pi}\right)^{1/2}$$

The migration velocity V_f is modeled as the product of a typical row velocity V* and its characteristic deepth L, i-e $V_f = V * L$

The loading rate $\dot{N}$ (Log/s) in the mean time is the product of the number of fuel rods per row N and their frequency V*

$$\dot{N} = V * N \qquad \text{and} \qquad V_f = \frac{\dot{N} L^2}{W} = \frac{\dot{N}\pi}{W\varepsilon_b} r^2$$

For computation purpose and since the objective of the investigation is to show the effect of the moisture content on the combustion parameters, it is rather $\rho_{water}\pi r_o^2\ell$ useful to express V_f in terms of the dry fuel rate Lr (kg/s).

$$\dot{N} = \frac{Lr}{1 - mc} \tag{3}$$

The final expression of V_f at any moisture content (≠ 100 %) is

$$V_f = \frac{Lr}{\left(1 - mc^2\right) S_g \rho_{water} W \ell \varepsilon_b}\left(\frac{r}{r_0}\right)^2$$

SOLID PHASE EQUATIONS

The objective of this chapter is to find an equation for the surface temperature (Ts) of the char under heterogeneous combustion and in the mean time find an explicit relation for the char layer thickness bc. This submodel has been described in references [3,4] and will not be repeated here for the shake of shortness. The only difference is the introduction of a factor 2 in the char layer thickness expression of chunkwood in order to keep with the fact that whole tree are long cylinders not spheres like chunkwood. The relation of the char layer thickness is then,

$$b_c = \frac{K_c(T_s - T_i)}{\rho_w(\varepsilon_v hfg_v + \varepsilon_m hfg_m) + \frac{Kc(T_s - T_i)}{2r}} \qquad (4)$$

GAS PHASE EQUATIONS

The products of the incomplete combustion at the char-gas interface (CO for the most part) and the fraction of volatiles that may have escaped early combustion now go to complete combustion in the gas phase. A sizable portion is burned inside the bed. It is assumed that the fraction of the total amount of gases produced that actually burn inside the bed is γ the remaining is burned by secondary air above the bed of fuel [2].The preheated air with maximum prescribed concentration at the bottom of the bed moves in countercurrent to the flow of solid fuel. Neglecting higher order terms, the following mass and heat balance equations are used to model the gas phase.The axial oxygen balance is given as

$$V_s \frac{dC}{dz} = -\dot{m}''_{o2}\left(\frac{A}{V_{ol}}\right) \qquad (5) \qquad \varepsilon_b \frac{2\pi r\ell}{\pi r^2 \ell} = \frac{2\varepsilon_b}{r}$$

(A/V_{ol}) is the surface to volume ratio. Referring to figure 3a

$$\frac{A}{V_{ol}}(m^2 fuel/m^3 fuel\ cell) = \frac{m^3_w}{m^3_{fc}} \frac{m^2_w}{m^3_w}$$

The oxygen mass flux $\dot{m}''_{o2}$ is obtained as [3, 4]

$$\dot{m}''_{02} = -\dot{m}/(iA) = -\left[\rho_c \frac{dr}{dt} + (\rho_w - \rho_c)\left(1 - \frac{b_c}{r}\right)\frac{dr_w}{dt}\right]\left(\frac{1}{i}\right)$$

where i is the stoichiometric index (12/16)

Equation (5) becomes then,

$$\rho_g \mathrm{Cpg} V_s \frac{dT_g}{dz} = -\rho_w \dot{r}\ \frac{2\varepsilon_b}{r}\left[(\varepsilon_c + \varepsilon_v)\gamma\ \mathrm{Hag} - \sum_{j=1}^{3} \varepsilon_j \mathrm{Cp}_j(T_s - T_j) - (\varepsilon_v \mathrm{hfg}_v + \varepsilon_m \mathrm{hfgm})\right] \quad (7)$$

$$V_s \frac{dC}{dz} = V_f \left[\rho_c \frac{dr}{dz} + (\rho_w - \rho_c)\left(1 - \frac{b_c}{r}\right)\frac{dr_w}{dz}\right]\frac{2\varepsilon_b}{ri} \quad (6)$$

$$\mathrm{Hag} = \frac{\left[(\varepsilon_c H_c + \alpha\varepsilon_v H_v)(1-\beta) + (1-\alpha)\varepsilon_v H_v\right]}{(\varepsilon_c + \varepsilon_v)}$$

Now neglecting radiation, the conservation of energy in the gas phase may be written as

where Hag is the average complete heat of combustion of the gases defined as.

Where :

ε_i is the mass fractions [3],

α is the fraction of the volatiles which burn to CO at the char-gas interface

β is the ratio of the heat of combustion of C to CO to that of C to CO_2

RESULTS AND DISCUSSION

The model equations are solved iteratively starting from the bottom of the bed, assuming a constant thermal properties, table 1.At the fuel exit, the combustion is assumed completed and taken to correspond to a 99% weight loss. The residual char and ash are collected under the grate.

Of particular importance for the design of wood boiler furnaces is the burnout time that is the actual residence time, and the combustion zone depth. Figures 4 to 7 show selected results of our investigation for fuel elements of radius equal to 0.2540 m down to particles fuel of 0.10 mm radius. The burnout time and combustion zone depth are found to be a function of both the fuel element size and their moisture content, Figures 4 and 5. The results of the model show that fuel elements of 10 cm radius at 33.3% moisture content take approximately 40 min to burnout with a combustion zone depth of 3.26m. Utilizing the best combustion models available to extrapolate for larger wood and higher moisture content and using log with 10 cm radius at 33.3% mc and data from actual whole tree facility, the RTI did found a burnout time of 40 min and a combustion zone depth of 3.60 m which are similar to the results of this model. We should not forget, however, that there are many assumptions to the model, the most severe being the uniform core temperature. As a matter of fact this is a simplified model, and the first part of series of papers that will be published later. Other assumption that we made in developing the model is that the transient warm up regime is neglected compared to the total burnout time. The data reported accordingly are those of the actual combustion period. The temperatures are shown to be not only a function of the fuel element properties (size and moisture content) and flow characteristics but also a function of the amount of volatiles α and maximum amount of gases γ that burn respectively at the char surface and inside the bed. Higher flame and surface temperatures are provided by the drier elements, while wet wood takes longer to burnout and produces depressed temperatures, figures 6 and 7.

This is so because a higher moisture means higher transpiration hence higher chilling effect. Furthermore, a large portion of the heat generated must be used for phase change of the fuel moisture from liquid water to vapor. The same pattern has been observed by A. Barriga and R.H. Esssenhigh [6] and by J. A. Mardani and al. who also found when studying the effects of the governing parameters on the time to ignition and weight loss that moisture content increases the time to ignition. It is said that this increase is due to the energy used in evaporating the additionnal water [7]. The model predicts rather adequatly the temperature range reported by the RTI which also found fuel moisture to significantly reduce boiler efficiency in the same "Whole tree"burn facility. Drier fuel elements provide the best input with increased heat release rate, smaller required furnace volume and subsequantly reduce boiler cost.

CONCLUSION

The simplified "Whole tree" fixed-bed model predicts rather well the burnout time and the combustion zone depth of a combustor of 100 Mw facility combusting 10 cm radius "Whole tree" fuel elements. The proper determination of the burnout time allows a rigorous scaling of the volume of the boiler furnace and subsequantly the calculations of the boiler heat release rate and efficiency. The shrinking core burning rate submodel is simple and yet reliable enough to show that the fuel elements moisture content is an important parameter in "Whole tree" burn as it may affect directly boiler cost and efficency.

Table I : Constant thermal properties

Properties	***Values***	***Units***	***References***
C_{pc}	0.670	kJ/kg-°K	8
C_{pm}	4.20	kJ/kg-°K	
C_{pv}	1.1	kJ/kg-°K	8
D	3.15 x 10^{-4}	m^2/sec	9
hfg_m	2250	kJ/kg	
hfg_v	200	kJ/kg	
H_c	31,100	kJ/kg	
H_v	13,500	kJ/kg	10
K_c	0.41x10^{-4}	kW/m-°K	9
ρ_c	95	kg/m^3	9
S_g	0.64	-	9
T_i	25	°C	9
ρ_b	240	kg/m^3	2
m_a	5.5	kg air/kg wet fuel	2
Lr	56.5	ton/h	2
ℓ	9.144	m	2
w	4.572	m	2
K	0.225	-	2
H	4.572	m	2

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