# Performance Evaluation of a Pilot Scale Vortexing Fluidized Bed Combustor

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Abstract–To understand vortexing fluidized bed combustor (VFBC) performances, an investigation was carried out a 0.45 m diameter and 4.45 m height pilot scale VFBC. Rice husks, corn, and soybean were used as the biomass e in a 0.45 m diameter and 4.45 m height pilot scale VFBC. Rice husks, corn, and soybean were used as the biomass feedstock and silica sand serving as the bed material. The bubbling bed temperature was controlled by using water injected into the bed. The experimental results show that the excess air ratio is the dominant factor for combustion efficiency. The in-bed combustion proportion increases with the primary air flow rate and bed temperature, and decreases with the volatile/fixed carbon ratio. The stability constant is proposed to describe the inertia characteristics of the vortexing fluidized bed combustor. The experimental results indicate that the stability of the VFBC increases with bed weight and primary air flow rate, but decreases with bed temperature.

Key words: Vortexing Fluidized Bed Combustor, Combustion Proportion, Biomass, Stability

## **INTRODUCTION**

An improved fluidized bed combustion technique, known as the vortexing fluidized bed combustor (VFBC), has been developed for use as a small- or medium-scale boiler or incinerator. The concept of VFBC was originally presented by Sowards [1977]. It was consisted of a vortex-generating system which was formed by injecting secondary-air tangentially into the freeboard. To increase the residence time of unburned carbon in the freeboard and prevent the elutriation of fine particle from the fluidized bed, an integration of combustor and cyclone was developed by Korenberg [1983]. Based on Korenberg's concept, the vortexing fluidized bed combustor was developed and named by Nieh and Yang [1987]. The characteristics of the VFBC can be represented by the swirl flow within the freeboard.

Numerous experimental and theoretical works have been carried out to investigate the coal combustion mechanism in fluidized combustors in developing an efficient model for large scale fluidized bed combustors. Most of the published data concentrated on the carbon combustion mechanism. To simplify this problem, char or coal particles with low ash content were used in those studies to represent carbon particles. The volatile matter is assumed to be burned quickly [Atimtay, 1987]. Since the volatile matter is responsible for about 40% of the heat released in the combustor, it is imperative to know how fast volatile matter is released from the feedstock.

is greater than that of any other renewable energy. The gasification conversion process can be expected to supply a substantial portion Biomass feedstock contains high volatile material content, 70- 90% for woods vs. 30-45% for typical coals [Schiefelbein, 1989]. The potential contribution of biomass to the world's energy needs of this contribution. However, the source and transportation costs for biomass materials restrict the amount of biomass that can be delivered to a central facility. In Taiwan, most farms are small and

separated; therefore, instead of gasification, combustion may be a promising technology for biomass treatment. Previous research concentrated primarily on biomass gasification [Mariani et al., 1992; Miles and Miles, Jr., 1989].

Fluidized bed combustors have excellent heat and mass transfer characteristics, which have led to fluidization use in many large scale processes, such as fluidized catalytic cracking and fluidized coal combustion. Understanding and predicting the behavior of the fluidized bed process is often limited by our understanding of the underlying fluid-solid mixture mechanism. Instability manifests in gas fluidized beds as "bubbles." Bubbles are caused by the dynamics of particle movement. Bubbles reduce the contact efficiency between the fluid and particles and the heat and mass transfer. A two-fluid model linear equation has been used to investigate the stability of uniform fluidization [Pigford and Baron, 1965; Anderson and Jackson, 1968]. A nonlinear model has also been employed for analysis [Needham and Merkin, 1983; Ganser and Drew, 1990]. Most of these works were conducted from the micro-mechanism viewpoint.

The aim of this study is to understand the characteristics of a pilot scale VFBC for biomass combustion. In this study, the combustion efficiency, combustion proportion and bed stability are investigated under various operating conditions.

#### **THEORY**

#### 1. Combustion Proportion

Fixed carbon was assumed burning in the bubbling bed. To know how the heat transfer surface should be arranged within the combustor to maintain a homogeneous temperature distribution, it is necessary to understand the heat proportion released in various sections in the combustor.

To simplify the mathematical calculation procedure, the following assumptions are made:

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<sup>(1)</sup> The combustor is divided into three sections: bubbling bed,



Fig. 1. Schematic diagram of three sections in combustor.

splash zone and freeboard (as showing in Fig. 1). Each section is assumed a continuous stirred tank reactor (CSTR).

(2) The specific heat of the flue gas (not including the water component) is similar to air.

(3) A drying process takes place in the bed.

(4) All of the water injected into the combustor is vaporized near the water injection location.

The mass balance of each section is shown as:

$$
F_{in,i-1} + F_{air,i} + F_{feed,i} + F_{H_2O,i} - F_{out,i} = 0
$$
\n(1)

The energy balance of each section is shown as:

$$
Q_{c,i} + Q_{in,i} - Q_{out,i} - Q_{L,i} = 0
$$
 (2)

Where

$$
Q_{in,i} = F_{ab,i}(1-C) \int_{T_{ref}}^{T_{ab}} C p_{ab} dT + F_{ab,i} C \int_{T_{ref}}^{T_{ab}} C p_{H,O(g)} dT + F_{H,O,i} \int_{T_{ref}}^{T_{H,O}} C p_{H,O(i)} dT ] + Q_{out,i-1}
$$
\n(3)

ponent) is similar to an:  
\n(3) A drying process takes place in the bed.  
\n(4) All of the water injected into the combustor is vaporized near  
\nthe water injection location.  
\nThe mass balance of each section is shown as:  
\n
$$
F_{in,i-1} + F_{air,i} + F_{feed,i} + F_{f,co,i} - F_{out,i} = 0
$$
 (1)  
\nThe energy balance of each section is shown as:  
\n $Q_{e,i} + Q_{in,i} - Q_{out,i} - Q_{L,i} = 0$  (2)  
\nWhere  
\n $Q_{in,i} = F_{air,i}(1-C) \int_{T_{ref}}^{T_{air}} C p_{at} dT + F_{air,i} C \int_{T_{ref}}^{T_{air}} C p_{H,O(g)} dT$   
\n $+ F_{H,O,i} \int_{T_{ref}}^{T_{inO}} C p_{H,O(i)} dT] + Q_{out,i-1}$  (3)  
\n $Q_{out,i} = [F_{air,i}(1-C) + F_{f}(1-X_{H,O} - 9X_{H} \times y_{i})]$   
\n $\times \int_{T_{ref}}^{T_{i}} C p_{air} dT + [F_{air,i}C + F_{f}(X_{H,O} + 9X_{H} \times y_{i})]$   
\n $\times \int_{T_{ref}}^{T_{i}} C p_{H,O(g)} dT + F_{H,O,i} \times (\int_{T_{ref}}^{T_{i}} C p_{H,O(g)} dT + \lambda)$  (4)  
\n $Q_{L,i} = \frac{(T_{i} - T_{sh,i})}{(T_{tr} - T_{sh})} H_{i}$  (5)  
\n $\frac{T_{i}}{2 \pi T_{i} k_{i}} + \frac{(T_{e} - T_{e})}{2 \pi T_{2} k_{e}}$  (6)

$$
Q_{L,i} = \frac{(T_i - T_{str,i})}{\frac{(r_b - r_a)}{2\pi r_i k_i} + \frac{(r_c - r_b)}{2\pi r_i k_c}} H_i
$$
\n
$$
(5)
$$

$$
\times \int_{\tau_{\alpha}}^{\tau_{\alpha}} \mathbf{C} \mathbf{p}_{H_{z}O(g)} dT + \mathbf{F}_{H_{z}O,i} \times (\int_{\tau_{\alpha}}^{\tau_{\alpha}} \mathbf{C} \mathbf{p}_{H_{z}O(g)} dT + \lambda)
$$
(4)  

$$
Q_{L,i} = \frac{(\mathbf{T}_{i} - \mathbf{T}_{si,j})}{\frac{(\mathbf{T}_{b} - \mathbf{T}_{a})}{2\pi r_{1} k_{s} + \frac{(\mathbf{T}_{c} - \mathbf{T}_{b})}{2\pi r_{2} k_{c}}}\mathbf{H}_{i}
$$
(5)  

$$
\mathbf{r}_{1} = \frac{(\mathbf{r}_{b} - \mathbf{r}_{a})}{\ln(\frac{\mathbf{T}_{b}}{\mathbf{r}_{a}})}
$$
(6)

texing Fluidized Bed Combustor

\n
$$
r_2 = \frac{(r_c - r_b)}{\ln\left(\frac{r_c}{r}\right)}\tag{7}
$$

 is calculated using the iteration method based on the mass and energy balances.  $e_y$  is the external value of  $e_y$  is the external value of  $e_y$  balances.

The combustion proportion in each section is given by Eq. (8).

$$
X_{c,i} = \frac{Q_{c,i}}{\sum_{i=1}^{3} Q_{c,i}} \times 100\%
$$
 (8)

Where  $y_i$ <br>d  $y_i$  is ca<br>d  $y_i$  is ca<br>d energy 1<br>The com<br> $X_{c,i} = \frac{Q_i}{\sum_{i=1}^{3} C_i}$ <br>The temped. Integral<br>integrals from eased) of<br>**Stability**<br>To describility<br>is stability<br>is: (1) The Fe can be<br>(3) The sp while state energ is the extent of volatiles combustion in the i<sub>s</sub> exection,<br>icludical sing the iteration method based on the mass<br>balances.<br>
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is calculary ba<br>
is calculary ba<br>  $=\frac{Q_{c,i}}{\sum_{i=1}^{3}Q_{c,i}}$ <br>
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## 2. Stability Constant

To describe the stability of a bubbling fluidized bed combustor, the stability constant  $(τ)$  is proposed based on the following assumptions:

(1) The FBC bubbling bed is assumed to be a CSTR.

(2) The heat loss in the bubbling bed from the outside FBC surface can be neglected.

While step changing water injection is employed, the unsteady state energy balance can be expressed as:

$$
W_b C p_{sand} \frac{dT_b}{dt} = Q_{g\omega, b} - F_{out} \int_{298}^{T_b} C p_s dT
$$
 (9)

surface and  $C_{p_s}$  is the specific heat of flue gas.

(3) The specific heats, Cp, and Cp<sub>sano</sub>, are assumed to be constant.<br>While step changing water injection is employed, the unstead;<br>te energy balance can be expressed as:<br> $W_s C_{p,\text{osc}} \frac{dT_1}{dt_s} = Q_{\text{gas},s} - F_{\text{tot}} \int_{\text{cm}}^5 C$ Where the F<sub>out</sub> is the flow rate of the flue gas left from the bed<br>face and C<sub>p</sub>, is the specific heat of flue gas.<br>For mathematical algorithm convenience, the heat generated in<br>bubbling region, Q<sub>omab</sub>, is expressed by surface and Cp<sub>s</sub> is the specific heat of flue gas.<br>
For mathematical algorithm convenience, the bubbling region, Q<sub>senk</sub>, is expressed by t<br>
(T<sub>k,as</sub>) at the steady state. Therefore, Eq. (9) car<br>
the following:<br>
W<sub><sup>8</sub>C<sub>P</sub></sup></sub> For mathematical algorithm convenience, the heat generated in the bubbling region,  $Q_{g\omega,b}$ , is expressed by the final temperature<br>  $(T_{b,\infty})$  at the steady state. Therefore, Eq. (9) can be transformed into<br>
the following:<br>  $W_s C_{p,conf} \frac{dT_1}{dt} = F_{off} \int_{298}^{T_s} C_{p,} dT - F_{off} \int_{298}^{T_s} C_{$ the following: e can be<br>
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cp<sub>s</sub> is the spec Tb face and<br>For math<br>bubblin<br>w, w) at the<br>followin<br>W, Cp<sub>sana</sub><br>When th<br>med cons<br>W, Cp<sub>sana</sub><br> $\frac{dT_b}{dt} = -\frac{1}{V}$ <br>The  $\tau$  ca<br>ions as fc<br>I.C.<br>The stabi de Form de regneration de regneration de regneration de variant de variant de variant de la poste de variant de la poste de l Cp<sub>s</sub> is the specific heat of flue gas<br>
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steady state. Therefore, Eq. (9) ca<br>
g:<br>  $\frac{dT_b}{dt} = F_{out} \int_{298}^{T_{\text{bg}}} Cp_s dT - F_{out} \int_{298}^{T_s} Cp_s dT$ <br>
e variation in

$$
W_b C p_{sand} \frac{dT_b}{dt} = F_{out} \int_{298}^{T_{b,x}} C p_s dT - F_{out} \int_{298}^{T_s} C p_s dT
$$
 (10)

sumed constant. When the variation in bed temperature is small,  $Cp_s$  can be as-

$$
W_b C p_{sand} \frac{dT_b}{dt} = F_{out} C p_s [(T_{b,\infty} - 298) - (T_b - 298)]
$$
 (11)

$$
\frac{dT_b}{dt} = -\frac{F_{out}Cp_s}{W_bCp_{s,and}}(T_b - T_{b,\infty}) = -\frac{1}{\tau}(T_b - T_{b,\infty})
$$
(12)  
The  $\tau$  can be obtained by solving Eq. (12) with the initial con-  
ions as follows:  
I.C.  $t=0$ ,  $T_b=T_{b,0}$  (13)

The  $\tau$  can be obtained by solving Eq. (12) with the initial conditions as follows:  $\tau$  can be obtained by solving  $E_a$  (12) with the initial con-

$$
\mathbf{C.} \qquad \qquad \mathbf{t} = \mathbf{0}, \qquad \qquad \mathbf{T}_b = \mathbf{T}_{b,0} \tag{13}
$$

The stability constant can then be calculated by using Eq. (14).

$$
(T_{b,\infty})
$$
 at the steady state. Therefore, Eq. (9) can be transformed into  
the following:  

$$
W_b C_{P_{s, and}} \frac{dT_b}{dt} = F_{out} \int_{298}^{T_{b,\infty}} Cp_{,} dT - F_{out} \int_{298}^{T_{b}} Cp_{,} dT
$$
(10)  
When the variation in bed temperature is small, Cp<sub>s</sub> can be assumed constant.  

$$
W_b C_{P_{s, and}} \frac{dT_b}{dt} = F_{out} C_{P_s} [(T_{b,\infty} - 298) - (T_b - 298)]
$$
(11)  

$$
\frac{dT_b}{dt} = -\frac{F_{out} C_{P_s}}{W_b C_{P_{s, and}}} (T_b - T_{b,\infty}) = -\frac{1}{\tau} (T_b - T_{b,\infty})
$$
(12)  
The  $\tau$  can be obtained by solving Eq. (12) with the initial conditions as follows:  
I.C.  $t=0$ ,  $T_b=T_{b,0}$  (13)  
The stability constant can then be calculated by using Eq. (14).  

$$
\tau = -\frac{t}{\ln(\frac{T_b - T_{b,\infty}}{T_{b,0} - T_{b,\infty}})}
$$
  
3. Combustion Efficiency  
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## 3. Combustion Efficiency

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#### Fig. 2. Pro flow chart of vortexing fluidized hed combustor



For different combustion systems, different formulas have been<br>weloped to calculate the combustion efficiency. In this work, the<br>mbustion efficiency is defined as the ratio of actual heat released<br>the combustor to the the developed to calculate the combustion efficiency. In this work, the combustion efficiency is defined as the ratio of actual heat released in the combustor to the theoretical energy availability of a given feedstock and feed rate during the combustion process, i.e., Eq. (15).

$$
\eta = \frac{Q_c}{F_f L H V_{feed}} \times 100\%
$$
\n(15)

Where  $Q_c$  is the heat released in the combustor.

## 4. Experimental Approach

Where Q<sub>c</sub> is the heat released in the combustor.<br>**Experimental Approach**<br>A schematic diagram of the combustion system<br>The fluidizing air (primary combustion air) w<br>hp Roots blower and the secondary air was surp<br>bo blower A schematic diagram of the combustion system is shown in Fig. 2. The fluidizing air (primary combustion air) was supplied by a 15 hp Roots blower and the secondary air was supplied by a 7.5 hp turbo blower. The combustor was 0.45m in diameter and 4.45 m in height. It was fabricated of stainless steel 316 and insulated with 150 mm thick Kaowool ceramic fiber. The feed material was supplied with the screw feeders. The feeding rate was controlled by adjusting the rotation speed of the drive motors. The feeding material went into the combustor through a chute located about 0.45 m above the air distributor. The system temperature was controlled by using in-bed and freeboard water injection. For differ<br>reloped to<br>mbustion when the comb<br>dstock and<br> $\eta = \frac{Q_e}{F_f L H}$ <br>Where  $Q_e$ <br>**Experim**<br>A schema<br>The fluid hp Roots<br>bo blower ght. It was<br>bo blower ght. It was combined with the using in-<br>I went interved to assign t different<br>ped to ca<br>stion efflicombustdock and fe<br>combustdock and fe<br> $\frac{Q_c}{F_f L H V_{feca}}$ <br>ere  $Q_c$  is t<br>**seriment**<br>consumed the fluidizin<br>Roots blower. The variance of the same of the same of the gas v<br>as cooled<br>flue gas v a Fig. Roots blower 12. Strew feeder<br>2. Orifice meter 12. Strew feeder<br>4. Rootedr 14 Compressor<br>4. Recorder 14 Compressor<br>5. Manumeter 16 Cyclome<br>6. The<br>monometre 15 Secondary air 20 Secondary in the heat exchanger<br>7. Tusto

The flue gas went through the air pollution control devices (APCD) and was cooled to about 200 °C before discharge into the atmosphere. The particulates in the flue gas were trapped by using two cyclones and a wet scrubber.

For a given operating condition, the temperature of the combustor was controlled by the in-bed injection water flow rate. Steady state was achieved when the temperature profiles were constant. Once the steady state condition was reached, the fly ash from the cyclones was weighed and collected for analysis. The operating conditions are summarized in Table 1.

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## Table 1. The experimental conditions



## Table 2. The properties of feedstock



The feedstock used in this study were rice husks, corn and soybean biomass. Silica sand was used as the fluidized material. The approximate and ultimate analyses and physic properties of the feedstock are listed in Table 2.

## RESULTS AND DISCUSSION

#### 1. Temperature Distribution

The temperature distribution profiles within the combustor at various excess air ratios are shown in Fig. 3. Two peaks are observed on the temperature profile. The first is at 0.8 m above the gas distributor. This peak can be attributed to the large amount of volatile material ignited in this section. The second peak is just above the



Fig. 3. Temperature distribution in the VFBC with various primary air flow rates (corn=15.9 kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, secondary air flow rate=0.6 Nm<sup>3</sup>/<br>min, feeding purge air=0.2 Nm<sup>3</sup>/min). static bed height=0.24 m, secondary air flow rate=0.6  $Nm<sup>3</sup>/$ static bed height=0.24 m, secondary air flow rate=0.6 Nm<sup>3</sup><br>min, feeding purge air=0.2 Nm<sup>3</sup>/min). min, feeding purge air= $0.2$  Nm<sup>3</sup>/min). min, feeding purge air=0.2 Nm3



Fig. 4. Effect of primary air flow rate on combustion proportion (corn=15.9 kg/hr, soybean=18.6 kg/hr, static bed height=  $0.24$  m, secondary air flow rate=0.6 Nm<sup>3</sup>/min, feeding purge air=0.2 Nm<sup>3</sup>/min, temperature=800 °C).

secondary air injection location. This peak is caused by the combustion of unburned carbon and volatiles resulting from the fresh injected air. The results, shown in Fig. 3, demonstrate that to maintain the bed temperature at  $800^{\circ}$ C, the amount of water injected with primary air must be increased. This is attributed to the in-bed combustion proportion increasing with the excess primary air ratio.

Because the volatile and ignited carbons are nearly exhausted at the exit and the heat was lost from the combustor surface, the temperature detected at the freeboard exit is lowest.

#### 2. Combustion Proportion

Fig. 4 shows the primary air flow rate effect on the combustion proportion. The results shown in Fig. 4 reveal that the in-bed combustion proportion increases significantly with the increase in primary air flow rate. This is attributed to the increase in excess air and combustible mixing with the air as the primary air flow rate increases. Both factors, excess air and mixing, can enhance the reaction rate of combustibles with air in the bed. The results obtained in this study are in agreement with that obtained by Bautista-Margulis et al. [1996]. (corn=15.9 kg/hr, soybean=18.6 kg/hr, static bed height=<br>0.24 m, secondary air flow rate=0.6 Nm<sup>2</sup>/min, feeding purge<br>air=0.2 Nm<sup>3</sup>/min, temperature=800 °C).<br>secondary air injection location. This peak is caused by the co 0.24 m, secondary air flow rate=0.6 Nm<sup>3</sup>/min, feeding purge air=0.2 Nm<sup>3</sup>/min, temperature=800 °C).<br>
air=0.2 Nm<sup>3</sup>/min, temperature=800 °C).<br>
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of unburned carbo 0.24 m, secondary air now rate=0.6 Nm<sup>3</sup><br>air=0.2 Nm<sup>3</sup>/min, temperature=800 °C<br>air=0.2 Nm<sup>3</sup>/min, temperature=800 °C<br>ary air injection location. This peak is c<br>of unburned carbon and volatiles resulu<br>air. The results, sho C).<br>
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crease in e air=0.2 Nm<br>ary air injectified of unburned<br>air. The rest<br>bed temperimary air multion proportial<br>and the heat<br>and the heat<br>and the heat<br>at edeted at 1<br>4 shows the pion. The resule proportion is<br>in flow rate.<br>Some proportion /min, temperature=800 on<br>on location. This peak is<br>l carbon and volatiles rest<br>lts, shown in Fig. 3, demot<br>ature at 800 °C, the amoust be increasing with the exc<br>ile and ignited carbons are<br>was lost from the combus<br>he free cau dimensional divided as a control of the cause of the capacity of the relation of the capacity of the control of the relationship of the capacity of the control of the control of the control of the control of the contro

Fig. 5 shows the bed temperature effect on the combustion proportion in each section. The combustion proportion in the bubbling region increases with the bed temperature. This is attributed to the



Fig. 5. Effect of bed temperature on combustion proportion (corn= 15.9 kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, primary air flow rate=2 Nm<sup>3</sup>/min, secondary air flow rate=  $0.6$  Nm<sup>3</sup>/min, feeding purge air= $0.2$  Nm<sup>3</sup>/min).

higher reaction rate at higher bed temperature.

Corn and soybeans exhibit different volatile/fixed-carbon ratios. The volatile/fixed-carbon ratio can be adjusted by changing the corn and soybean feed rates. The results, as shown in Fig. 6, demonstrate that the combustion proportion in the bubbling region decreases with the volatile/fixed-carbon ratio. This is in agreement with the statement that most of the fixed carbon is burned in the bubbling bed and most volatiles are burned in the freeboard.

For the same test, the volatile/fixed-carbon ratio was adjusted by changing the rice husk and soybean feed rates, respectively. The combustion proportion in the bubbling region increases with increasing volatile/fixed-carbon ratio, as shown in Fig. 7, which is contrary to the result shown in Fig. 6. This is attributed to the higher elutriation rate of rice husks because of its lower density. Rice husks rose with the gas flow and burned in the freeboard. As shown in Figs. 6 and 7, the results demonstrate that the feedstock characteristics significantly affect the combustion proportion in each section. Fig. 5. Effect of bed temperature on combustion proportion (corn= **primary air flow rate=2 Nm**<sup>2</sup>/min, secondary air flow rate=0.6 Nm<sup>2</sup>/min, secondary air flow rate=0.6 Nm<sup>2</sup>/min, feeding purge air=0.2 Nm<sup>2</sup>/min).<br>
The constrained the different colatile/fixed-carbon ratios.<br>
Italie/fix primary air now rate=2 Nm<br>0.6 Nm<sup>3</sup>/min, feeding purge<br>reaction rate at higher bed ten<br>and soybeans exhibit differe<br>latile/fixed-carbon ratio can be<br>bean feed rates. The results, a<br>e combustion proportion in the volatile/f air=0.2 Nm<sup>3</sup>/min).<br>
air=0.2 Nm<sup>3</sup>/min).<br>
apperature.<br>
ent volatile/fixed-carbon ratios.<br>
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## 3. Combustion Efficiency

Combustion behavior is represented by the combustion efficiency. Therefore, the effects of various operating parameters on the combustion efficiency are investigated in this section. Fig. 8 shows the primary air flow rate effect on the combustion efficiency when the secondary air flow rate is kept constant. From Fig. 8, the combustion efficiency increases with the increase in primary air flow rate.



Fig. 6. Effect of volatile/fixed carbon ratio on combustion proportion (corn=0-35.1 kg/hr, soybean=0-33.1 kg/hr, static bed height=0.24 m, bed temperature=800 °C, excess air ratio= 40%, in-bed stoichiometric air ratio=100%, feeding purge air= $0.2$  Nm<sup>3</sup>/min).

This is attributed to higher turbulence and in-bed excess air ratio caused by increasing the primary air flow rate. Higher turbulence and in-bed excess air lead to better gas-solid contact and higher oxygen mass transfer rate to the fuel particle surface. Therefore, the char combustion rate in the bubbling bed increases as the superficial velocity increases [Winter et al., 1997]. These results also imply that the oxygen concentration and gas-solid mixing in the bed are the dominant factors for combustion.

The effect of in-bed stoichiometric air percent ratio on the combustion efficiency at a given excess air ratio of 40% was studied (Fig. 9). From Fig. 9, the deviation between the maximum and minimum combustion efficiency values is within 3%. Therefore, we can state that the in-bed stoichiometric air percent ratio (or primary to secondary air ratio) effect can be neglected. The bed height effect (or bed weight) on the combustion efficiency, as shown in Fig. 10, is also minimal. In these two experiments, the superficial gas velocities and combustion temperatures were kept the same; therefore, the combustible residence times in the combustor were similar. Two most important factors in combustion efficiency (combustion temperature and residence time) were not changed with the varying of experimental variables. Consequently, the combustion efficiencies are not changed with the in-bed stoichiometric air percent ratio and bed height. secondary air ratio) effect can be neglected. The bed height effect (or bed weight) on the combustion efficiency, as shown in Fig. 10, is also minimal. In these two experiments, the superficial gas velocities and combustio height=0.24 m, bed temperature=800 °C, excess air ratio=40%, in-bed stoichiometric air ratio=40%, feeding purge air=0.2 Nm<sup>3</sup>/min).<br>40%, in-bed stoichiometric air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/min).<br>4tirbuted to height=0.24 m, bed temperature=800<br>40%, in-bed stoichiometric air ratio=1<br>40%, in-bed stoichiometric air ratio=1<br>air=0.2 Nm<sup>3</sup>/min).<br>attributed to higher turbulence and in-<br>by increasing the primary air flow rate<br>bed exce 00%, feeding purge<br>bed excess air ratio<br>
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1. The same in the bed maximum an air=0.2 Nm<sup>3</sup>/min).<br>attributed to higher turbulence and in-bed excess air ratio<br>by increasing the primary air flow rate. Higher turbulence<br>by increasing the primary air flow rate. Higher turbulence<br>ord excess air lead to air=0.2 Nm<br>attributed to<br>by increasing<br>attributed to<br>by increasing<br>ord excess air<br>ass transfer rambustion rat<br>ocity increase<br>except computation effect of in-b<br>efficiency at<br>. From Fig. 9,<br>combustion e that the in-b<br>weight highe g the p lead t to in the p lead t to in the lead t to in the S [Wire center of the s lead t a give the d strike the connect the connect the connect the induced strike in the induced strike in the induced strike in th

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Fig. 7. Effect of volatile/fixed carbon ratio on combustion proportion (rice husk= $0-41.6$  kg/hr, sovbean= $0-33.1$  kg/hr, static bed height=0.24 m, bed temperature=800 °C, excess air ratio=40%, in-bed stoichiometric air ratio=100%, feeding purge air= $0.2$  Nm<sup>3</sup>/min).

To understand the volatile/fixed-carbon ratio effect on the combustion efficiency, corn and soybean mixtures were used as the feedstock. The volatile/fixed-carbon ratios were adjusted by changing the corn feed rate range from 0 to 35.1 kg/hr and the soybean range from 0 to 33.1 kg/hr. According to the results shown in Fig. 11, the combustion efficiency increased with the increase in volatile/fixedcarbon ratio. This is caused by the amount of unburned char particles. In this study, the heat losses are considered two possibilities, the apparatus heat loss from the surface of combustor and the unburned char particle elutriated. The higher the volatile/fixed carbon ratio leads the less unburned char particles discharge. Consequently, the low probability for char particles elutriation and high volatile combustion rate, the overall combustion efficiency will increase with the volatile/fixed-carbon ratio. This statement is in agreement with the results of Paul et al. [1993], obtained from a fluidized bed combustor using coal of various rank as the feedstock. They found that the higher the fixed carbon content, the lower the combustion efficiency. the volatile/fixed-carbon ratio. This statement is in agreement with<br>the results of Paul et al. [1993], obtained from a fluidized bed com-<br>bustor using coal of various rank as the feedstock. They found that<br>the higher the bed height=0.24 m, bed temperature=800 °C, excess air ratio=40%, in-bed stoichiometric air ratio=100%, feeding<br>purge air=0.2 Nm<sup>3</sup>/min).<br>mderstand the volatile/fixed-carbon ratio effect on the com-<br>efficiency, com and soy bed negm=0.24 m, bed temperature=800<br>
de negm=0.24 m, bed temperature=800<br>
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efficiency, corn and soy **purge air=0.2 Nm'/min).**<br> **nderstand** the volatile/fixed-carbon ratio effect on the con-<br>
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efficiency, com and soybean mixtures were adjusted by denaping<br>
the v purge air=0.2 Nm<br>nderstand the volati<br>efficiency, corn and<br>The volatile/fixed-ca<br>n feed rate range fro<br>to 33.1 kg/hr. Accor<br>stion efficiency increase<br>in this study, the heat l<br>us heat loss from the<br>use heat loss from the<br>p

## 4. Bed Stability

One of the most important advantages of the fluidized bed combustor (FBC) is the bed temperature inertia. The bubbling bed serves as a heat reservoir, maintaining bed temperature while the feedstock heating value is always changing. The stability constant,  $\tau$ , is used



Fig. 8. Effect of primary air flow rate on combustion efficiency (corn=15.9 kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, secondary air flow rate= $0.6$  Nm<sup>3</sup>/min, feeding purge air = $0.2$  Nm<sup>3</sup>/min, temperature= $800$  °C).



Fig. 9. Effect of in-bed stoichiometric air percent ratio on combustion efficiency (static bed height=0.24 m, primary air flow rate=2.0 Nm<sup>3</sup>/min, excess air ratio=40%, feeding purge air= 0.2 Nm<sup>3</sup>/min, temperature= $800 °C$ ).

to represent the stability of the fluidized bed. A higher stability constant implies that the system is more stable.

The stability constant,  $\tau$ , was calculated from the bed temperature history variation data produced by the step change in cooling water injected into the bed. The step change of cooling water injection worked as a disturbance of feedstock heating value. When a certain set combustion condition was achieved, the rate of cooling water injection would be changed suddenly and sustained this new change. The dynamic behaviors of bed temperature change were collected and analyzed via Eq. (14). The bed weight, primary air rate and initial bed temperature effects on the stability were investigated. rate=2.0 Nm<sup>3</sup>/min, excess air ratio=40%, feeding purge air=0.2 Nm<sup>3</sup>/min, temperature=800 °C).<br>Sent the stability of the fluidized bed. A higher stability consent the stability of the fluidized bed. A higher stability co rate=2.0 Nm<br>0.2 Nm<sup>3</sup>/min<br>9.2 Nm<sup>3</sup>/min<br>sent the stabi<br>plies that the<br>stability cons<br>tory variation<br>injected into tworked as a<br>n set combus<br>ter injection v<br>ange. The dyn<br>d and analyze<br>ial bed tempe /min, excess air ratio=40%, feeding purge air= 0.2 Nm<br>sent the phies that<br>stability variged is stability<br>worked in set contexned in the contexned in the contexned of the example. The contexned is also the example.  $m$ **min, temperature=800** or<br>stability of the fluidized be<br>at the system is more stable<br>constant,  $\tau$ , was calculate<br>iation data produced by th<br>mot the bed. The step chases a disturbance of feedst<br>mbustion condition was ed. .<br>ed. .<br>e. d fi ie s<br>mgcock<br>chicale terd v<br>tabi

All of the experiments conducted for the stability test were pre-



Fig. 10. Effect of static bed height on combustion efficiency (corn= 15.9 kg/hr, soybean=18.6 kg/hr, bed temperature=800 °C, primary air flow rate=2.0 Nm<sup>3</sup>/min, excess air ratio=40%, in-bed stoichiometric air percent ratio=100%, feeding purge air= $0.2$  Nm<sup>3</sup>/min).



Fig. 11. Effect of volatile/fixed carbon on combustion efficiency (corn=35.1-0 kg/hr, soybean=0-33.1 kg/hr, static bed height =0.24 m, bed temperature=800 °C, excess air ratio=40%, in-bed stoichiometric air ratio=100%, feeding purge air  $=0.2$  Nm<sup>3</sup>/min).

ceded using a fuel-feeding rate of 15.9 kg/hr for corn and 18.6 kg/ hr for soybeans. Most of the experiments were conducted at a 40% excess air ratio (variables of bed weight and bed temperature). When a step change in water injection (0.1 L/min) was employed, the bed temperature vs. time data were recorded and analyzed. A typical result is shown in Fig. 12. The stability constant,  $\tau$ , is in agreement with a first order equation, as shown in Eq. (14). corn=35.1-0 kg/hr, soybean=0-33.1 kg/hr, static bed height<br>=0.24 m, bed temperature=800 °C, excess air ratio=40%,<br>in-bed stoichiometric air ratio=100%, feeding purge air<br>=0.2 Nm<sup>3</sup>/min).<br>ceded using a fuel-feeding rate of =0.24 m, bed temperature=800 °C, excess air ratio=40%,<br>in-bed stoichiometric air ratio=100%, feeding purge air<br>=0.2 Nm<sup>3</sup>/min).<br>
sing a fuel-feeding rate of 15.9 kg/hr for corn and 18.6 kg/<br>
ybeans. Most of the experiment =0.24 m, bed temperature=800<br>in-bed stoichiometric air ratio=<br>=0.2 Nm<sup>3</sup>/min).<br>sing a fuel-feeding rate of 15.9 kg<br>ybeans. Most of the experiments<br>ir ratio (variables of bed weight an<br>anange in water injection (0.1 L/min<br> 2) The set of the same state in the set of 100%, feeding purge air sylum (100%, feeding purge air divided ded temperature). When all was employed, the bed and analyzed. A typical pustant,  $\tau$ , is in agreement 1. (14). ta =0.2 Nm<sup>3</sup>/min).<br>
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anange in water inject =0.2 Nm<br>sing a fuel<br>ybeans. M<br>ir ratio (va<br>aange in w<br>ture vs. tij<br>shown in Fi<br>pht. This is<br>er the bed<br>er the bed

As shown in Fig. 13, the stability constant,  $\tau$ , increases with the bed weight. This is attributed to heat sink effect in the bed. The bed heat capacity increases when the bed weight increases. In other words, the higher the bed weight, the less sensitive the bed is to tempera780



Fig. 12. Typical temperature changes in bed after increasing water injected by step change (corn=15.9 kg/hr, soybean=18.6 kg/hr, excess air ratio=40%, in-bed stoichiometric air ratio=100%, feeding purge air=0.2  $Nm<sup>3</sup>/min$ ).



Fig. 13. Effect of bed weight on stability constant (corn=15.9 kg/ hr, soybean=18.6 kg/hr, excess air ratio=40%, in-bed stoichiometric air ratio=100%, feeding purge air=0.2  $Nm<sup>3</sup>/$ min, temperature=800 °C, U/U<sub>m</sub>=10.9).

ture (feedstock heating value) changes.

From Fig. 14, one can find that at a certain temperature the stability constant increases with the flow rate of primary air. And from Fig. 15 the results illustrate that the stability constant decreases with bed temperature. The stability constant is indicative of the speed of response of the process and depends on the operating conditions. In this study, we have only limited information on the effects of primary air flow rate and bed temperature. The simple tests of this study are not enough to interpret completely and accurately. Therefore, further studies are needed to clarify these phenomena. Even though the mechanisms of the bed temperature stability are not clear, an empirical correlation is developed to predict the bed temperature Fig. 13. Entroposition and the stability constant in the stability constant  $\mathbf{R}$  and  $\mathbf{S}$  and  $\$ ichiometric air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/<br>nichiometric air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/<br>min, temperature=800 °C, U/U<sub>m</sub>=10.9).<br>Stock heating value) changes.<br>Fig. 14, one can find that at a certa ichiometric air ratio=100%, feeding purge air=0.2 Nm<sup>2</sup><br>min, temperature=800 °C,  $U/U_{mj}$ =10.9).<br>dstock heating value) changes.<br>Fig. 14, one can find that at a certain temperature the sta<br>nstant increases with the flow rat / min, temperature=800<br>dstock heating value) cha<br>Fig. 14, one can find tha<br>mstant increases with the f<br>he results illustrate that the<br>perature. The stability con<br>of the process and depe<br>udy, we have only limited<br>flow rate an Example 2.1 and the same of primal standard and the estability constant is indicatively and accuracy the same position of the predict of the predict of the predict of the predict the same of the predict the same of the pr

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Fig. 14. Effect of primary air flow rate on stability constant (corn= 15.9 kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, secondary air flow rate= $0.6 \text{ Nm}^3/\text{min}$ , feeding purge air = $0.2$  Nm<sup>3</sup>/min. temperature= $800$  °C).



Fig. 15. Effect of bed temperature on stability constant (corn=15.9) kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, secondary air flow rate=0.4 Nm<sup>3</sup>/min, in-bed stoichiometric air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/min, U/U<sub>mi</sub>=  $10.9$ ).

stability constant. Using regression analysis, a relation

$$
\tau = 4.588 \times 10^{-4} \times \frac{(W_b + 258.51)(Q_i + 1.2105 \times 10^{-3}(T_b + 273.15))}{(T_b + 273.15)^{5/3}}
$$
\n(16)

was obtained that correlates all of the experimental data obtained in this study with an average deviation of 2.1%, and standard deviation of 3.0%, as shown in Fig. 16. The agreement between the estimated values and the experimental data is good. ondary air flow rate=0.4 Nm<sup>3</sup>/min, in-bed stoichiometri<br>air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/min, U/U<sub>m/</sub><br>10.9).<br>bility constant. Using regression analysis, a relation<br> $\tau$ =4.588×10<sup>-4</sup>× $\frac{(W_b + 258.51)(Q_i + 1.2105 \times$ The Train-Holomontairead is and the experimental data obtained with an average since the experimental data obtained with an average deviation of 2.1%, and standard deviation with an average deviation of 2.1%, and standard kg/hr, soybean=18.6 kg/hr, static bed height=0.24 m, secondary air flow rate=0.4 Nm<sup>3</sup>/min, in-bed stoichiometric<br>air ratio=100%, feeding purge air=0.2 Nm<sup>3</sup>/min, U/U<sub>m</sub>=<br>10.9).<br>Stability constant. Using regression analys ondary air how rate-0.4 Nm<br>air ratio=100%, feeding purg<br>10.9).<br>constant. Using regression anal<br>588×10<sup>-4</sup>× $\frac{(W_b + 258.51)(Q_t + 1)}{(T_b + 258.51)(Q_t + 1)}$ <br>ained that correlates all of the<br>udy with an average deviation of<br>.0%, as **e air=0.2 Nm<sup>3</sup>/min, U/U<sub>mg</sub>=<br>
lysis, a relation<br>
1.2105 × 10<sup>-3</sup> (T<sub>b</sub>+273.15))<br>
+273.15)<sup>5/3</sup> (16)<br>
experimental data obtained<br>
of 2.1%, and standard devia-<br>
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is good.<br>
ON** air ratio=100%, feeding purge air=0.2 Nm<br>10.9).<br>
constant. Using regression analysis, a relation<br>
588 × 10<sup>-4</sup> ×  $\frac{(W_b + 258.51)(Q_1 + 1.2105 \times 10^{-3}(T_6 + 273.15)^{5/3}}{(T_b + 273.15)^{5/3}}$ <br>
ained that correlates all of the expe  $\frac{N_b + 273.15)}{m_g}$  (16)<br>data obtained<br>andard devia-<br>ween the esti-

#### **CONCLUSION**



Fig. 16. Comparison between experimental and predicted stability constant.

In this study, the bed temperature within a combustor was controlled by using water injected into a fluidized bed combustor. The bed excess air ratio was the major parameter for combustion efficiency. The combustion efficiency increased with the increase in primary air flow rate (excess air ratio) bed temperature and feedstock volatile/fixed carbon ratio. The bed height effect on the combustion efficiency was minimal.

A higher combustion proportion within a bubbling bed can be obtained by increasing the bed temperature or primary air flow rate. The combustion proportion within the bed decreased with the volatile/fixed carbon ratio when the feedstock was mixture of soybeans and corn. This is in agreement with our inference. However, the combustion proportion within the bed increased with the increase in volatile/fixed carbon ratio when the feedstock was a mixture of rice husks and soybeans. Rice husk elutriation into the freeboard was the dominant factor for heat released in the freeboard.

The inertia of a fluidized bed combustor can be represented by the stability constant, which increases with the bed weight, primary air flow rate, and decreases with the bed temperature. An empirical correlation was proposed to express the relationship between the stability constant and operating conditions such as bed weight, bed temperature and primary air flow rate. The agreement between the estimated values and experimental data is good. The inertia of a fluidized bed combustor can be represented by<br>the inertia of a fluidized bed combustor can be represented by<br>the istability constant, which increases with the bed temperature. An empirical<br>correlation was

#### **NOMENCLATURE**

 $C$  : moisture of air [kg/kg]

 $Cp_{air}$ : specific heat capacity of air [kcal/kg-°C]

 $Cp_{a_k}$ : specific heat capacity of air [kcal/kg-<sup>o</sup><br> $Cp_{H_2O(l)}$ : specific heat capacity of liquid water<br> $Cp_{H_2O(l)}$ : specific heat capacity of gaseous wa<br> $Cp_s$ : specific heat capacity of flue gas [kca<br> $Cp_{sand}$ : specific Cp<sub>H<sub>2</sub>O(l)</sub>: specific heat capacity of liquid water [kcal/kg<sup>-o</sup>C] Cp<sub>H<sub>2</sub>O(g): specific heat capacity of flue gas [kcal/kg<sup>-o</sup>C] Cp<sub>samd</sub>: specific heat capacity of flue gas [kcal/kg<sup>-o</sup>C] Cp<sub>samd</sub>: specific heat capaci</sub>  $Cp_{H<sub>2</sub>O(1)}$ : specific heat capacity of liquid water [kcal/kg °C]

- $Cp_{H_2O(\epsilon)}$ : specific heat capacity of gaseous water [kcal/kg<sup>o</sup>C]
- Cp<sub>H<sub>2</sub>O(g): specific heat capacity of gaseous water [kcal/kg-°C]<br>Cp<sub>sand</sub>: specific heat capacity of flue gas [kcal/kg-°C]<br>Cp<sub>sand</sub>: specific heat capacity of sand [kcal/kg-°C]<br> $F_{air}$  : air mass flow rate [kg/min]<br> $F_{f}$ </sub> Cp<sub>sand</sub>: specific heat capacity of flue gas [kcal/kg-°C]<br>Cp<sub>sand</sub>: specific heat capacity of sand [kcal/kg-°C]<br>F<sub>air</sub> : iair mass flow rate [kg/min]<br> $F_f$  : feeding rate [kg/min]<br> $F_{H_2O}$  : injection water flow rate [kg/  $C_{p_{s}}$ : specific heat capacity of flue gas [kcal/kg<sup>o</sup>C]
- $Cp_{\text{start}}$ : specific heat capacity of sand [kcal/kg-°<br>  $F_{\text{air}}$  : air mass flow rate [kg/min]<br>  $F_f$  : feeding rate [kg/min]<br>  $F_{H_2O}$  : injection water flow rate [kg/min]<br>  $F_{\text{in}}$  : input gas mass flow rate [kg/min]  $Cp_{\text{stand}}$ : specific heat capacity of sand [kcal/kg-°C]
- $F_{air}$  : air mass flow rate [kg/min]
- $F_{c}$  $F_{f}$  : feeding rate [kg/min]<br>  $F_{H_2O}$  : injection water flow r<br>  $F_{in}$  : input gas mass flow r : feeding rate  $\lceil \text{kg/min} \rceil$
- $F_{air}$  : air mass flow rate [kg/min]<br>  $F_f$  : feeding rate [kg/min]<br>  $F_{H_2O}$  : injection water flow rate [k]<br>  $F_{in}$  : input gas mass flow rate [k]  $F_{H_2O}$ : injection water flow rate  $\lceil \frac{kg}{min} \rceil$
- $F_{H_2O}$  : injection water flow rate [kg/min]<br> $F_{in}$  : input gas mass flow rate [kg/min]  $F_{\scriptscriptstyle in}$  $F_{in}$  : input gas mass flow rate [kg/min] : input gas mass flow rate [kg/min]

 $F_{tot}$  : output gas mass flow rate [kg/min]<br>  $H_{tot}$  : height of the tih section [m]<br>  $K_k$  : thermal conductivity of sec. 316 [kg]<br>  $K_k$  : thermal conductivity of sec. 316 [kg]<br>  $K_k$  : thew rate of primary air [Nm<sup>1</sup>/min]<br> : output gas mass flow rate [kg/min]  $F_{out}$  $H<sub>i</sub>$ H<sub>i</sub> : height of the ith section [m]<br>  $\mu$ , thermal conductivity of s.s.<br>  $\mu$ , thermal conductivity of section<br>  $\mu$ , thermal conductivity of section<br>
LHV<sub>*R<sub>NC</sub>I*</sub> : wet base low heating valu<br>  $Q_i$  : flow rate of primar : height of the ith section [m]  $k_{\rm s}$ : thermal conductivity of s.s. 316 [kcal/m-min-°C] ks.  $\therefore$  thermal conductivity of s.s. 316 [kcal/m-min-2<br>ks.  $\therefore$  thermal conductivity of seramic fiber [kcal/m-min-2<br>LHV<sub>n-1</sub>: wet base low heating value of Feedstock [kcal/m-min-of thermal conductivity of external [Nm<sup></sup>  $k_{c}$ : thermal conductivity of ceramic fiber [kcal/m-min-°C] kc  $\mu$  : thermal conductivity of ceramic fiber [keal/m-min-official/m-min-official/m-min-official/m-min-official/m-min-official/m-min-official/m-min-off-min-off-min-off-min-off-min-of-min-of-min-of-min-of-min-of-min-of-m LHV $_{\text{feed}}$ : wet base low heating value of feedstock [kcal/kg] LHV<sub>6ee</sub>: 1 the base low heating value of feedstock [kcal/kg] Q.  $\therefore$  the base of pinnary air [Nm/min]<br>Q.  $\therefore$  flow nate release in combustor [kcal/min]<br>Q.  $\therefore$  then release of ith section [kcal/min]<br>Q.  $\therefore$  then tele  $Q_1$  : flow rate of primary air [Nm<sup>3</sup>/min] Q<sub>c</sub> : total heat release in combustor [kcal/min]<br>
Q<sub>c</sub> : heat release of ith section [kcal/min]<br>  $Q_0$  : theat loss with flue gas exhausting [kcal/min]<br>  $Q_0$  : input heat [kcal/min]<br>  $Q_0$  : input heat [kcal/min]<br>  $Q_0$  $Q_{c,i}$ Q<sub>c</sub>, : heat release of ith section [kcal/min]<br>
Q<sub>cm</sub>, i heat loss with flue gas exhusting [kcal/min]<br>
Q<sub>cm</sub>, i heat generation form the dombustor O<sub>g</sub>, beat loss with flue gas exhusting [kc],<br>
Q<sub>m</sub> : i temperature of int : heat release of ith section [kcal/min] : heat loss with flue gas exhausting [kcal/min]  $O_{\epsilon}$ Q<sub>1</sub> : heat loss with flue gas echancing [kcal/min]<br>
Q<sub>2</sub> : heat generation from fuel combuston in bed<br>
Q<sub>2</sub> : heat loss from surface of combustor [kcal/min]<br>
Q<sub>2</sub> : heat loss from surface of combustor [kcal/min]<br>
L<sub>3</sub> : Qgen,  $\therefore$  their generation from fitted Combustion in bed [kcal/min]<br>
Qg. : heat loss from surface of combustor [kcal/min]<br>
Qg. : heat loss from surface of combustor [kcal/min]<br>
L<sub>is</sub> : temperature of initi air ["C]<br>
T<sub>i</sub>  $Q_n$  : input heat [kcal/min]<br>  $Q_L$  : heat loss from surfac<br>  $Q_{nm}$  : output heat [kcal/min]<br>  $Q_L$  : output heat [kcal/min]<br>  $T_{nn}$  : temperature of inlet is check in the subsequent of inlet is chemperature [°C]  $T_{n,\sigma}$  : Q<sub>L</sub> : heat loss from surface of combustor [kcal/min]<br>  $Q_m$  : output heat [kcal/min]  $T_{\text{av}}$  : temperature of linet ari ["C]<br>  $T_{\text{av}}$  : bed temperature [°C]<br>  $T_{\text{av}}$  : final bed temperature [°C]<br>  $T_{\text{av}}$  : infina  $Q_{out}$  : output heat [kcal/min]<br>  $Q_{out}$  : output heat [kcal/min]<br>  $T_{ab}$  : temperature of inlet air<br>  $T_{b}$  : initial bed temperature [°C]<br>  $T_{b}$  : initial bed temperature  $T_{b}$ <br>  $T_{b}$  : itemperature of the ith  $T_{H_{20$ : temperature of inlet air  $[°C]$  $T_{ab}$  : temperature of inlet air  $[{}^{\circ}$ <br>  $T_{ab}$  : the temperature  $[{}^{\circ}C]$ <br>  $T_{b}$ , initial bed temperature  $[{}^{\circ}C]$ <br>  $T_{b}$ , initial bed temperature  $[{}^{\circ}C]$ <br>  $T_{b}$  : temperature of the ith section<br>  $T_{b}$  : te : bed temperature [°C] T<sub>b, 0</sub> : bed temperature [°<br>
T<sub>b, 0</sub> : initial bed temperat<br>
T<sub>b, $\omega$ </sub> : final bed temperat<br>
T<sub>p</sub>, is emperature of the<br>
T<sub>p,</sub> : reference temperat<br>
T<sub>r<sub>p</sub></sub> : reference temperat<br>
r<sub>p</sub> : reference temperat<br>
r<sub>p</sub> : emperat  $T_{b,\omega}$  : initial bed temperature [ $\binom{n}{k}$  : initial bed temperature [ $\binom{n}{k}$  : temperature of the ith sector<br> $T_{h,\omega}$  : temperature of the ith sector<br> $T_{H,\omega}$  : temperature of injected  $\binom{n}{k}$  : reference temperat : initial bed temperature  $[°C]$ : final bed temperature  $[°C]$  $T_{b,\omega}$ : final bed temperature [°<br>  $T_{H_2O}$ : temperature of the ith s<br>  $T_{H_2O}$ : temperature of injected<br>  $T_{H_2O}$ : temperature of injected<br>  $T_{m}$ : reference temperature,<br>  $T_{m}$ : reference temperature,<br>  $T_{m}$ : loga : temperature of the ith section  $[°C]$ T<sub>L<sub>RO</sub></sub>: temperature of the ith section [<sup>o</sup>]<br>
T<sub>LRO</sub></sup>: temperature of injected water [<sup>o</sup>]<br>
T<sub>LRO</sub> : reference temperature, 25 °C [<sup>o</sup>]<br>
temperature of combustor surfa<br>
r<sub>La</sub> : temperature of combustor surfa<br>
r<sub>L</sub><sub>T</sub> :  $T_{H<sub>2</sub>0}$ : temperature of injected water [°C]  $T_{H_2O}$  : temperature of injected water  $[{}^n_1_{m'}]$  : reference temperature, 25 °C  $[{}^n_2_{m'}]$  : temperature of combustor surfains  $T_{m'}$  : togarithmic mean radius [m] :  $T_{m}$  : togarithmic mean radius [m] :  $T_{m}$  :  $T_{rw}$  : reference temperature, 25 or<br>  $T_{rw}$  : temperature of combustor  $r_n$ <br>  $T_{rw}$  : logarithmic mean radius [n<br>  $r_s$  : inner diameter of combusts<br>  $T_{sw}$  : inner diameter of combusts<br>  $T_{sw}$  : outer diameter of combus C [°C] T<sub>urr</sub> : temperature of combustor surface [<sup>o</sup><br>
r<sub>1</sub> : logarithmic mean radius [m]<br>
r<sub>2</sub> : logarithmic mean radius [m]<br>
r<sub>1</sub> : uner diameter of combustor [m]<br>
r<sub>1</sub> : outer diameter of combustor [m]<br>
r<sub>3</sub> : bed weight [kg] : temperature of combustor surface  $[°C]$  $r_1$  : logarithmic mean radius [m]<br> $r_2$  : logarithmic mean radius [m]  $r_2$  : logarithmic mean radius [m]<br> $r_a$  : inner diameter of combustor [m] r<sub>a</sub> : inner diameter of combustor [m]<br>  $r_a$  : outer diameter of combustor [m]<br>  $r_b$  : outer diameter of combustor will<br>  $N_{H_2O}$  : bed weight [kg]<br>  $X_{e,i}$  : combustion proportion of the ith<br>  $X_{H_2O}$  : weight percenta r<sub>b</sub> : outer diameter of combustor [m]<br>
v. betweight [kg]<br>
V. betweight [kg]<br>
X.<sub>t.</sub>, : combustion proportion of the ith<br>
X.<sub>t.</sub>, : combustion proportion of the ith<br>
X.<sub>t.</sub>, : weight percentage of water in fect<br>
x.<br>
y. iv r. couter diameter of combustor with insulation [m]  $W_a$  : bed weight [kg]<br>  $W_{A,\nu}$  : combustion proportion of the ith section [-]  $X_{\mu,\nu}$  : weight percentage of water in feedstock [-]  $X_{\mu}$  : weight percentage of We W<sub>b</sub> : bed weight [kg]<br>
X<sub>e,*i*</sub> : combustion pro<br>
X<sub>H<sub>2</sub></sub> : weight percenta<br>
X<sub>H</sub> : weight percenta<br>
Y<sub>i</sub> : weight percenta<br>
: combustion extic<br>
: combustion effi<br>
: latent heat of w<sub>i</sub><br>
: stability constant<br>
T : stabil  $X_{\mu,\rho}$  : combustion proportion of the ith section [-]<br>  $X_{\mu,\rho}$  : weight percentage of water in feedstock [-]<br>  $X_{\mu}$  : weight percentage of H element in feedstock<br>  $Y_{\mu}$  : combustion extent of volatiles in the ith  $X_{H_2O}$  : weight percentage of water in feedstock [-]<br>  $X_H$  : weight percentage of H element in feedstock [-]<br>  $\eta$  : combustion extent of volatiles in the ith sec<br>  $\eta$  : combustion efficiency [-]<br>
2 : latent heat of w  $\eta$  : combustion efficiency [-]<br> $\lambda$  : latent heat of water [kcal/

- $\lambda$  : latent heat of water [kcal/kg]<br>  $\tau$  : stability constant [min]
- : stability constant [min]

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- $X_n$  : weight percentage of H element in feedstock [-]<br>
7, : combustion extent of volatiles in the ith section<br>
7, : combustion efficiency [-]<br>
2. i.latent heat of water [kcal/kg]<br>
7. i.latent heat of water [kcal/kg]<br>
7. y<sub>i</sub> : combustion extent of volatiles in the ith section [-1]<br>
7 : combustion efficiency [-1]<br>
2 : contoustion efficiency [-1]<br>
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