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Combustion Characteristics of a Hot Water Boiler System Convertibly Fueled by Rice Husk and Heavy Oil - Heavy Oil Combustion Characteristics -

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Abstract

Purpose: With the ever-rising energy prices, thermal energy heavily consuming facilities of the agricultural sector such as commercialized greenhouses and large-scale Rice Processing Complexes (RPCs) need to cut down their energy cost if they must run profitable businesses continually. One possible way to reduce their energy cost is to utilize combustible agricultural by-products or low-price oil instead of light oil as the fuel for their boiler systems. This study aims to analyze the heavy oil combustion characteristics of a newly developed hot water boiler system that can use both rice husk and heavy oil as its fuel convertibly. **Methods:** Heavy oil combustion experiments were conducted in this study employing four fuel feed rates (7.6, 8.5, 9.5, 11.4 l/h) at a combustion furnace vacuum pressure of 500 Pa and with four combustion furnace vacuum pressures (375, 500, 625, 750 Pa) at fuel feed rates of 9.5 and 11.4 l/h. Temperatures at five locations inside the combustion furnace and 20 additional locations throughout the whole hot water boiler system were measured to ascertain the combustion characteristics of the heavy oil. From the temperature measurement data, the thermal efficiency of the system was calculated. Flue gas smoke density and concentrations of air-polluting components in the flue gas were also measured by a gas analyzer. **Results:** As the fuel feed rate or combustion furnace vacuum pressure increased, the average temperature in the combustion furnace decreased but the thermal efficiency of the system showed no distinctive change. On the other hand, the thermal efficiency of the system was inversely proportionally to the vacuum level in the furnace. For all experimental conditions, the thermal efficiency remained in the range of 80.1-89.6%. The CO concentration in the flue gas was negligibly low. The NO and SO_2 concentration as well as the smoke density met the legal requirements. **Conclusions:** Considering the combustion temperature characteristics, thermal efficiency, and flue gas composition, the optimal combustion condition of the system seemed to be either the fuel feed rate of 9.5 l/h with a combustion furnace vacuum pressure of 375 Pa or a fuel feed rate of 11.4 l/h with a furnace vacuum pressure between 500 Pa and 625 Pa.

Keywords: Combustion, Heavy oil, Hot water boiler system, Rice husk, Thermal efficiency

Introduction

Currently, the two most concentrated energy consumption facilities in the domestic agricultural field are the greenhouses and RPCs. As of 2012, there are 236 RPCs having a milling capacity of over 6,000 ton in Korea (Anonymous, 2013). They rely heavily on light fuel as their heat source for facility heating and paddy drying. As for protected horticultural cultivation, the areas of plastic greenhouses equipped with heating facility and large-scale commercialized greenhouses in 2012 were 9,500 ha and 2,900 ha, respectively (Anonymous, 2013). Most of such protected horticultural facilities also use light oil as fuel for their heaters and hot water boilers, with the annual fuel consumption and cost estimated to be about 110 x 10^6 L and 50 billion won, respectively.

With the ever-rising energy prices, these facilities

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need to cut down their thermal energy cost to be able to run profitable business continually. One possible way to reduce their energy cost is to utilize combustible agricultural by-products or low-price oil instead of light oil as their thermal energy source. Among many agricultural by-products, rice husk has been recognized as a good thermal energy source through direct combustion. In a hot water boiler system where rice husk is used as a fuel for its combustion furnace, it is reported that the system not only reaches steady state in a relatively short time but also responds successfully to the external thermal load fluctuation (Park, 2001). Use of a rice husk furnace, however, may pose the danger of insufficient seasonal supply of rice husks, while some technical problems specific to rice husk combustion can occur during operation. Thus, the rice husk furnace would be better if it is also able to operate with an alternative fuel.

This study therefore aims to analyze the heavy oil combustion characteristics and system performance of a newly developed hot water boiler system which can use both rice husk and heavy oil convertibly as its fuel.

Materials and Methods

The heavy oil (No. 6 oil) used in the experiment was purchased from an oil refinery company. Its chemical composition, heating values, and density are shown in Table 1. The chemical composition and density measurement were done by the Jeonju Center of the Korea Basic Science Institute. The higher level heating value was measured with a bomb colorimeter (1341EB, Parr Instrument Co., U.S.A.), and the lower level heating value was calculated based on measured higher level heating value and chemical composition.

Table 1. Chemical composition, heating value, and density of heavy oil (No. 6 oil) used in the study

Chemical composition (%)						
Ash	Carbon	Hydrogen	Nitrogen	Sulfur	Others	Total
0.04	86.00	11.40	0.30	1.70	0.56	100.0
Heating value (kJ/kg)				Density (kg/m^3)		
Higher heating value: 45,200				927.3 (@30oC)		
Lower heating value: 43,100				903.3 (@70oC)		

Combustion furnace and hot water boiler system

The combustion furnace and hot water boiler system used in this study was convertibly fueled by rice husk and heavy oil (Figure 1). It was designed and developed to target the thermal load of about 1,100,000 kJ/h required by a typical 3,300 m^2 size greenhouse (Park, 2001). Considering the physicochemical and combustion characteristics of the major fuel, the rice husk, a vertical cylindrical-shaped fixed-bed type furnace without air swirl, was used. Rice husk transport from the storage tank to the furnace and ash removal from the bottom of the furnace were both operated pneumatically. The system was equipped with three heat-exchanging components to recover the necessary heat energy from fuel combustion.

A burner (FNP55, F.B.R. Inc., Italy) was installed in the furnace for heavy oil combustion. The direction of fuel injection from the burner was angled 5^o downward to the horizontal plane and 10^o sideways to the vertical central axis of the furnace. This setting helped the injected fuel particles to extend their combustion duration and also the flames to swirl along the inside wall of the furnace, resulting to an increase in combustion heat recovery by the wall water jacket.

The combustion furnace was made of cast iron since the furnace, when rice husk used for fuel not only underwent an extremely high temperature condition

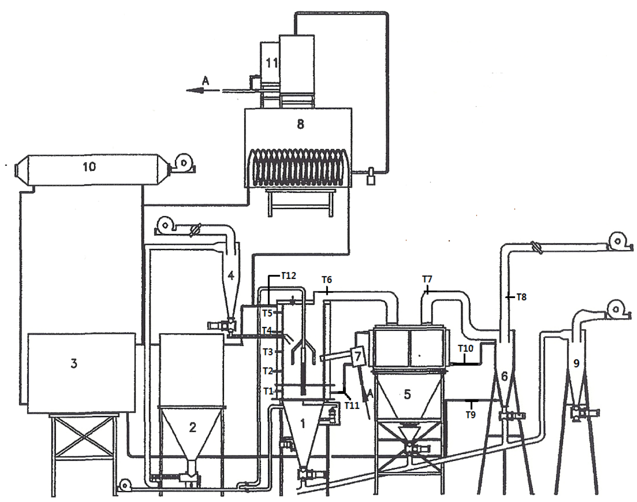

Figure 1. Schematic diagram of a combustion furnace and hot water boiler system convertibly fueled by rice husk and heavy oil (T1-T12 are temperature measurement locations): ① combustion furnace, ② rice husk tank, ③ hot water tank, ④ rice husk feeding cyclone, ⑤ shell-and-tube heat exchanger, ⑥ flue gas-borne ash collecting cyclone, ⑦ oil burner, ⑧ heavy oil tank, ⑨ rice husk ash collecting cyclone, ⑩ radiator, ⑪ light oil tank.

during initial ignition period but also experienced a periodic cycle of high and low temperatures on its lower part during normal operation. In the rice husk ash discharge hopper which was attached to the bottom of the combustion furnace, a differential pressure transmitter (Type 40, JUMO GmbH and Co., Germany) was installed to measure the inside pressure of the combustion furnace. These measurements were used to adjust the openness of the flue gas discharge damper in order to control the negative pressure level in the combustion furnace.

To supply the thermal energy generated from fuel combustion to any demanding facilities, a general purpose shell-and-tube heat exchanger was manufactured and installed as the main heat recovering equipment in the hot water boiler system because of its easy maintenance and high overall heat transfer coefficient. The rectangular parallelepiped shell-and-tube heat exchanger had an overall dimension of 2,000 x 1,000 x 1,000 mm (L x W x H); its tube side was consisted of 64 SUS pipes ($\phi = 53\,mm$) which were arranged in 8 x 8 matrix form. Besides by the shell-and-tube heat exchanger, the combustion heat was also recovered at the combustion furnace and at the flue gas-borne ash collecting cyclone by installing a water jacket on their walls.

The hot water boiler system had a main and a supplementary fuel tank both equipped with an internal heating device because of low heavy oil viscosity at ambient temperature. There was another light oil tank (400 L capacity) in the system since diesel fuel should be used for the starting and finishing stages of heavy oil combustion, which was a common practice.

Combustion experiment

The main factors that affect the combustion characteristics of a liquid fuel furnace were generally known to be the fuel feed rate and the degree of vacuum in the furnace (Kim, 2002). Based on findings from preliminary tests, combustion experiments were conducted with two replications for four fuel feed rates (7.6, 8.5, 9.5, 11.4 L/h) at a combustion furnace vacuum pressure of 500 Pa and four combustion furnace vacuum pressures (375, 500, 625, 750 Pa) at fuel feed rates of 9.5 and 11.4 L/h.

At the start of the combustion experiment, the induced draft fan for flue gas discharge was turned on as the discharge duct damper opened. The burner was then turned on and light oil was injected into the furnace and ignited to bring about combustion. After about 10 minutes of initial combustion with light oil, the fuel line switch on the control panel was toggled and heavy oil began to be supplied to the burner. Combustion experiment then proceeded while the openness of the flue gas discharge duct damper was adjusted automatically with a stepping motor in order to keep the combustion furnace vacuum pressure at a predetermined value.

Once the whole system reached a steady-state condition, the temperatures at five locations (T1-T5) inside the combustion furnace and 20 additional locations (T6-T25) throughout the hot water boiler system were measured by K-type thermocouples (Woojin Co., Korea) at every 15 minutes for two hours and recorded in a data acquisition board (CR-21X, Campbell Co., U.S.A.). Flow rate of water circulating through the system was measured by a digital flow meter and flue gas smoke density, and concentrations of air polluting components in the flue gas were measured by a gas analyzer (ECOM-A Plus, ECOM Ltd. U.S.A.) installed in a pipeline branched from the main flue gas discharge duct.

During heavy oil combustion experiments, the devices needed when rice husk was used as fuel, such as rice husk feeding cyclone, ash removal grate, and excess air supplying forced-draft fans, were turned off.

Results and Discussion

Temperature Characteristics

Figure 2 shows the mean temperature at each location (T1-T5) in the combustion furnace for various fuel feed rates at a furnace vacuum pressure of 500 Pa. The temperature at T3 was the highest and those at T1 and

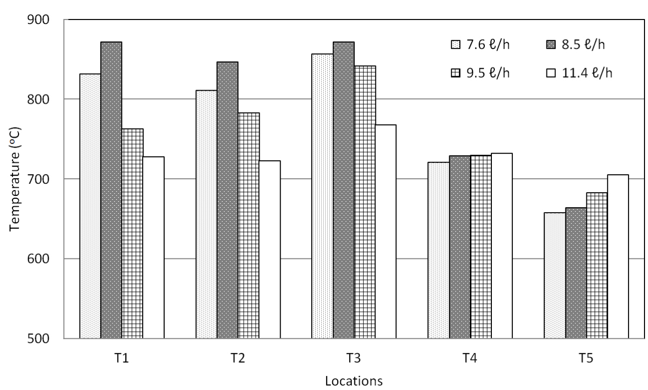

Figure 2. Mean temperatures at several locations inside the combustion furnace for various fuel feed rates (furnace vacuum pressure: 500 Pa).

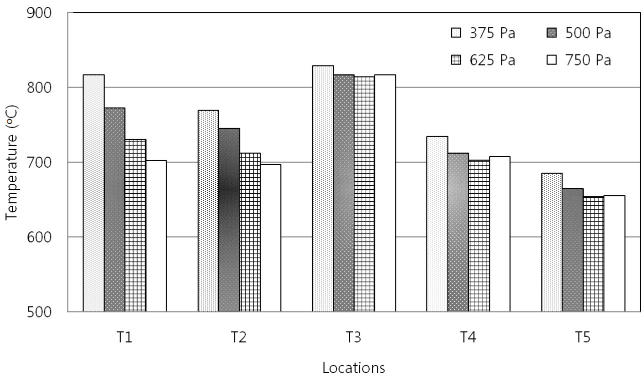

Figure 3. Mean temperatures at several locations inside the combustion furnace for various furnace vacuum pressures (fuel feed rate: 9.5 L/h).

T2 showed the next highest temperature since the flame was set to eject downward toward the T1 location even though it exited from the burner between T2 and T3. Going up the upper region in the furnace (T4, T5), the distance from the flame became farther and thus the temperatures were lower compared with those at T1-T3. As the fuel feed rates increased, the temperature difference between the upper and lower regions became smaller. This might be reasoned in that the territory of flame combustion was extended to the upper region in the furnace when more than enough fuel was injected.

Figure 3 shows the mean temperature at each location (T1-T5) in the combustion furnace for various vacuum pressures of the furnace at a fuel feed rate of 9.5 L/h. As the vacuum levels of the furnace increased, the temperatures of the lower region in the furnace decreased but the temperatures of the upper region changed little. The reason for this result was that the higher vacuum level in the furnace induced an increase in the air-fuel mixture gas velocity within the furnace and therefore the flame was propagated more quickly to the upper region of the furnace. For the fuel feed rate of 11.4 L/h, no significant difference in the temperature characteristics was found when compared with those obtained at the fuel feed rate of 9.5 L/h.

Thermal efficiency and flue gas characteristics

The heat recovery efficiency of the three heat exchanging components installed in this system was calculated using Eq. (1). The thermal efficiency of the system was defined as Eq. (2). It was basically the ratio of the quantity of heat recovered by the heat exchanging components to the quantity of heat generated from fuel combustion.

$$
\begin{aligned}
E_{com} &= \frac{\dot{m} \times c_p \times (T_{12} - T_{11})}{F \times LHV \times \eta_{ct}} \times 100(\%) \\
E_{sht} &= \frac{\dot{m} \times c_p \times (T_{11} - T_{10})}{F \times LHV \times \eta_{ct}} \times 100(\%) \\
E_{cyc} &= \frac{\dot{m} \times c_p \times (T_{10} - T_{9})}{F \times LHV \times \eta_{ct}} \times 100(\%)
\end{aligned} \tag{1}
$$

$$E_{system} = \eta_{ct} \times (E_{com} + E_{sht} + E_{cyc}) \times 100(\%) \tag{2}$$

where, E_{com}, E_{sht}, E_{cyc}: heat recovery efficiency of combustion furnace water jacket, shell-and-tube, and flue gas-borne ash collecting cyclone water jacket, respectively (%)

E_{system} : thermal efficiency of system (%)
$\dot{m}$: water circulation rate (kg/h)
c_p : specific heat of water (=4.18 kJ/kg°C)
T_9, T_{10} : water temperature at inlet and outlet of flue gas-borne ash collecting cyclone water jacket (°C)
T_{10}, T_{11} : water temperature at inlet and outlet of shell-and-tube heat exchanger (°C)
T_{11}, T_{12} : water temperature at inlet and outlet of combustion furnace water jacket (°C)
F : feed rate of heavy oil (L/h)
LHV : low level heating value of heavy oil (=43,100 kJ/kg)
η_{ct} : combustion efficiency of heavy oil (=1.0)

Figure 4 shows heat recovery efficiency depending on the fuel feed rates, with a combustion furnace vacuum pressure of 500 Pa. As the fuel feed rates increased, the heat recovery efficiency of the combustion furnace

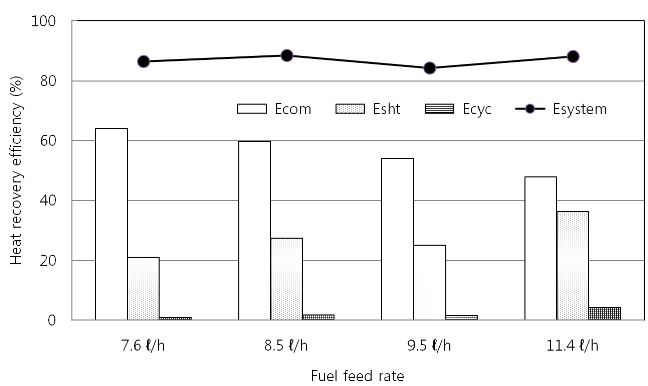

Figure 4. Heat recovery efficiencies of heat exchanging components and thermal efficiency of system for various fuel feed rates (furnace vacuum pressure: 500 Pa).

water jacket decreased but the heat recovery efficiency of the shell-and-tube heat exchanger increased.

As already shown in Figure 2, increase in the fuel feed rates made the temperature of the upper region in the furnace increase to some degree while the temperature of the lower region in the furnace decreased drastically; thus, the average temperature of the furnace was lower and this consequently resulted in the decreased heat recovery efficiency of the combustion furnace water jacket.

The thermal efficiencies of the system were 86.5, 88.5, 84.3, and 88.2%, respectively, which were satisfactory

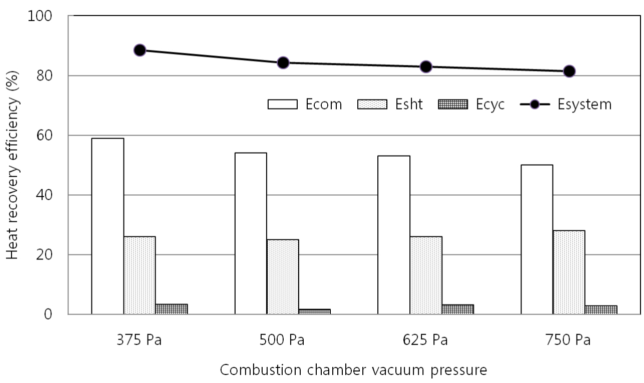

Figure 5. Heat recovery efficiencies of heat exchanging components and thermal efficiency of system for various combustion furnace vacuum pressures (fuel feed rate: 9.5 L/h).

in general when the fuel feed rates were 7.6, 8.5, 9.5, and 11.4 L/h. No distinctive relation between the thermal efficiency and fuel feed rate was seen.

Figure 5 shows heat recovery efficiencies depending on the vacuum level in the combustion furnace when the fuel feed rate was 9.5 L/h. As the vacuum level increased, the heat recovery efficiency of the combustion furnace water jacket decreased while that of both the shell-and-tube heat exchanger and the flue gas-borne ash collecting cyclone water jacket showed little change. This finding could be explained from the location dependency of the furnace temperature decrease with the furnace vacuum level increase as shown in Figure 3, going up from T1 to T5. The amount of temperature decrease due to the furnace vacuum level increase lessened.

The thermal efficiency of the system was inversely proportionally to the vacuum level in the furnace; the thermal efficiencies were 88.5, 84.3, 83.0, and 81.5% for the vacuum pressures of 375, 500, 625, and 750 Pa, respectively. The experimental results when the fuel feed rate was 11.4 L/h was qualitatively similar to those with the fuel feed rate of 9.5 L/h, giving the thermal efficiencies of 89.6, 88.2, 83.8, and 80.2% for the vacuum pressures of 375, 500, 625, and 750 Pa, respectively

As for the concentrations of air polluting components

Table 2. Concentrations of air polluting components in the flue gas for various fuel feed rates and combustion furnace vacuum pressures

Combustion conditions		Chemical components			Soot (Bacharach scale)
		CO (ppm)	NO (ppm)	SO_2 (ppm)	
7.6 L/h	375 Pa	n/a	n/a	n/a	n/a
	500 Pa	12	211	329	3
	625 Pa	n/a	n/a	n/a	n/a
	750 Pa	n/a	n/a	n/a	n/a
8.5 L/h	375 Pa	n/a	n/a	n/a	n/a
	500 Pa	12	200	265	3
	625 Pa	n/a	n/a	n/a	n/a
	750 Pa	n/a	n/a	n/a	n/a
9.5 L/h	375 Pa	11	192	319	4
	500 Pa	11	175	223	3
	625 Pa	9	163	153	3
	750 Pa	5	140	138	3
11.4 L/h	375 Pa	9	186	110	4
	500 Pa	3	167	113	4
	625 Pa	3	150	84	4
	700 Pa	6	135	82	3
Legal limit		350	250	540	4

in the flue gas, a compensation based on Eq. (3) was carried out on the measured data in accordance with the official method of analysis. The results are shown in Table 2.

$$Conc_{comp} = Conc_{meas} \times \frac{20.9 - O_{2_{ref}}}{20.9 - O_{2_{meas}}} \tag{3}$$

$Conc_{comp}$, $Conc_{meas}$: compensated and measured concentration, respectively (ppm)
$O_{2_{meas}}$: measured concentration of oxygen in flue gas (% vol.)
$O_{2_{ref}}$: reference concentration of oxygen in flue gas (=4% vol.)

For all combustion conditions, the quantity of CO in the flue gas was negligible. The major components of NOx and SOx in the flue gas were found to be NO and SO_2 and their contents did not exceed the legal limits. It is generally known that the NO concentration in flue gas varies depending on the combustion temperature to a large degree but the concentration of SO_2 is decided by various factors such as fuel feed rate, air supply quantity, combustion temperature, and other combustion conditions (Song and Choi, 1999). As shown in Table 2, the concentration of NO and SO_2 both decreased when the fuel feed rate or combustion furnace vacuum pressure increased. As mentioned earlier, the combustion experiments showed that the average temperature of the combustion furnace decreased when the fuel feed rate or combustion furnace vacuum pressure increased and this furnace temperature decrease could bring the decrease of the NO concentration of the flue gas. For all combustion conditions, the smoke densities of the flue gas were 3-4 in Bacharach smoke scale and did not exceed the legal limit.

Conclusion

For a combustion furnace and hot water boiler system that was convertibly fueled by rice husk and heavy oil, a study was made on its heavy oil combustion characteristics. Combustion experiments were conducted with fuel feed rate and combustion furnace vacuum pressure as the two chief experimental factors. The major findings were as follows.

(1) As the fuel feed rate or combustion furnace vacuum pressure increased, the average temperature in the furnace decreased but the thermal efficiency of the system showed no distinctive change. On the other hand, the thermal efficiency of the system was inversely proportionally to the vacuum level in the furnace. For all experimental conditions, the thermal efficiency remained in the range of 80.1-89.6%.
(2) Based on the findings on combustion temperature characteristics, thermal efficiency, and flue gas composition, it was thought that the optimal combustion condition of the system was the fuel feed rate of 9.5 L/h with a combustion furnace vacuum pressure of 375 Pa or a fuel feed rate of 11.4 L/h, with a combustion furnace vacuum pressure between 500 and 625 Pa.
(3) For all experimental conditions, the CO concentration in the flue gas was negligibly low. The NO and SO_2 concentrations, as well as the smoke density, met the legal requirements.

Conflict of Interest

The authors have no conflicting interests, financial or otherwise.

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