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Prototype Design of Paddy Straw Biomass Combustor for Water Heating

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An innovative prototype design of paddy straw biomass combustor with pilot fuel injection system has been developed and tested for boiling of water at domestic level. The innovation of mixing pilot fuel (diesel) intermittently (in small quantity) with blower air helped in flame sustainability to achieve complete combustion. A cylindrical furnace with conical top was designed for exit of flue gas from the top where a vessel containing 2 L of water was placed, which started boiling within 3 min and used for making tea. Experimental trials showed that each 3 kg bale took about 6-7 min for complete burning by achieving the flue gas temperature between 329 and 354°C. During the 8-10 h operation, the designed combustor had the potential for boiling rice and pulses at domestic level. The combustor could heat 40L of water per hour by utilizing about 250 kg of paddy straw and 120 ml of pilot fuel.

Key words: Bale, Combustor, Forced draft, Grate shaker, Paddy straw, Pilot fuel

Burning of paddy straw in the fields is a major problem in northern states of India due to which, environmental and soil based issues are created every year during the harvesting season of paddy. Complete combustion of paddy straw has been an issue of concern for its burning as biomass fuel in combustors. Improving the thermal as well as emissions performance of biomass cook stoves has been of interest to researchers for a long time. On a long run and for a sustainable path forward, biomass is seen as potential fuel. However, the cook stoves require huge improvements in terms of efficiency and low emission (Thakur *et al.*, 2015). Many studies on biomass combustors have been conducted. Yin *et al.* (2008) investigated the grate firing of biomass for the production of heat and power. Porteiro *et al.* (2010) experimentally analysed the ignition front propagation of several biomasses in fixed bed combustor. Powar *et al.* (2014) designed a gasifier based cookstove for improving the performance. Nandi *et al.*(2015) evaluated the performance of improved biomass cook stove to reduce emissions and for improving the overall quality of life. There was complete fuel consumption and removal of char and ash was easy due to the provision of grate with ash holder. Thakur *et al.* (2015) fabricated and analysed the performance of a biomass cookstove based on the principle of forced draft gasifier using single fan for high efficiency. Singh *et al.*(2015) performed the fluidized bed combustion of rice husk and paddy straw. Combustion of paddy straw reported more agglomeration problems when used alone. The ash content after combustion / gasification contained mainly silica. Zhang *et al.* (2015) studied the effects of fluidization velocity and equivalence ratio on energy and syngas produced from wheat straw in fluidized bed gasifier using dual distributor plate. Antony *et al.* (2016) deigned a downdraft biomass gasifier for the continuous burning of corn plantation blended with suitable agent. It was concluded that the biomass with light weight was better for gasification in the gasifier. Saturday *et al.* (2016) designed and thermally analysed energy efficient solid biomass cook stove to eliminate incomplete combustion to reduce toxic CO emissions.

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In this study, an attempt has been made to improve the combustion process of paddy straw biomass in the fixed bed combustor by employing intermit pilot fuel injection in a very small quantity for sustaining the flame to achieve complete combustion. It is pertinent to note that there is a major problem of handling the paddy straw in North Indian states as farmers resort to burn it in fields leading to many environmental and health issues. A motorized grate shaker with automatic combing operation to remove the fly ash from the grate has also been designed and used for smooth operation of the combustor. The flue gases generated have been tested for the cooking potential by boiling the hot water indicating the usefulness of the combustor for cooking and boiling applications.

Material and Methods

Combustor design

A cylindrical furnace of GI sheet having a height of 145 cm and a diameter of 55 cm was designed and installed at the Department of Mechanical Engineering, Punjab Agricultural University Ludhiana, India (Fig. 1 and Fig. 2). The top of the furnace was made conical and an opening of 9 cm for flue gas exit was provided at its top. A grate was fabricated using MS bar and fixed at a height of 30 cm from the bottom. A comber attached with grate shaker (1/4hp motor) helped in removing the fly ash through the reciprocating motion below the grate. A vessel containing water was placed at the top on a frame (fabricated for the purpose) for making direct contact with the hot flue gas at its bottom.

Pilot fuel injection system

A pilot fuel injection system operated with solenoid valve was used to deliver one mL fuel after every 3 min. time inside the cone of a variable speed blower consuming 380 W power and supplying forced air at a volumetric flow rate of $0.96 m^3 min^{-1}$ equivalent to 33.85 CFM. The fuel was stored in a 5L tank mounted on a stand at a height of 2m from the ground for supply to the fuel pump. The height of the tank provided pressure for fuel motion under the action of gravity. The air thrust from the blower cone helped in atomizing the pilot fuel (diesel) in small droplets pointed towards the bale for sustaining the flame.

Grate shaker

A grate shaker with comber was also designed and used for automatic removal of fly ash from the grate. It provided a reciprocating motion to the comber which in turn helped in removing the fly ash from the grate to the bottom of the furnace. A motor of 380 W was used to run the grate shaker. Schematic set-up of the developed prototype of paddy straw biomass combustor with pilot fuel injection system including fuel tank, solenoid operated pilot fuel injection pump and air blower with fuel mixing system is shown in Fig. 2a. The flame generated due to combustion as shown in Fig. 2b (with open door) was used for boiling 2 L of water put in a vessel and placed at the top of the furnace on a frame utilizing the heat from the flue gas.

Experimental considerations

Primary fuel used for combustion was paddy straw in baled form. Bigger bale of about 18 kg was cut into six pieces to make smaller bales of 3 kg weight per bale. Higher heating value of the used paddy straw (14.53 MJ kg^{-1}) was determined using a bomb calorimeter and proximate analysis was carried out using a high temperature muffle furnace, both of MAC make. Moisture content, volatile matter, fixed carbon and ash content in paddy straw was found to be 7.19%, 67.01%, 15.76% and 17.23%, respectively. Ultimate analysis was carried out using an Elementar make CHNS Analyser. C, H, N, O and S in paddy straw was found to be 40.41%, 6.23%, 1.05%, 34.98% and 0.1%, respectively.

One paddy straw bale was fed to the furnace through the door and inflamed manually. Thereafter, through automatic operation, metered quantity (one ml) of the pilot fuel was supplied through the solenoid operated fuel pump for sustaining the flame after every 3 min. Grate shaker was run continuously during the entire 30 min trial to remove the fly ash. The subsequent bales were fed to the furnace when the flame from the previous bale was just about to die out after about 6-7 min. Temperature of the water rise was measured after every 30 sec. using a stem-type alcohol based thermometer (0 to 250°C range). Temperature of the flue gas was measured after every 3 min. interval using Testo 340 flue gas analyser (measuring range of -40°C to 1200°C with an accuracy of ± 0.5%). After the complete burning of bales ash content was also measured, which was about 17.3% and found to be very close to the literature value of 18% establishing the fact of complete combustion of the paddy straw biomass.

Theoretical considerations

The paddy straw used in the study can be represented by the formula CH1.85O0.649. The global reaction for stoichiometric combustion of the paddy straw is given by the following equation

$CH_{1.85}O_{0.649}$+ 1.138O_2◊CO_2 + 0.925H_2O + heat(1)

The air-fuel ratio (AFR) involved in the combustion is represented by

$$AFR = \frac{m_{air}}{m_{fuel}} \quad (2)$$

Where m_{air} is the mass of the air introduced and m_{fuel} is the mass of the fuel In reality, some percent of air in excess of stoichiometric air is required for making the combustion more efficient and is represented by equivalence ratio (ø)

$$\phi = \frac{1}{\lambda} = \frac{AFR_{stoich}}{AFR_{actual}} \quad (3)$$

Where λ is the stoichiometric ratio, AFR_{stoich} and AFR_{actual} is the stoichiometric and actual air-fuel ratio. Percentage excess air (*n*) is represented by

$$n = (\lambda - 1) \times 100 \quad (4)$$

Total heat (Q_{total}) released by combustion of a fuel ($MJkg^{-1}$) is given by

$$Q_{total} = m \times HCV \quad (5)$$

Where m is mass of the fuel (kg) and HCV is higher calorific value of the fuel (in MJ kg^{-1})

Heat available (Q_{av}) from combustion (in $MJkg^{-1}$) for raising the temperature is given by

$$Q_{av} = m \times LCV \quad (6)$$

Sensible heat required to raise the temperature of waterbyΔT(30°C to 100°C) is given by

$$Q = m \times C_p \times \Delta T \quad (7)$$

Where Cp is the specific heat capacity of water (4.18 KJ kg^{-1} K^{-1})

Results and Discussion

Combustion characteristics and heat gain by water

Stoichiometric air-fuel ratio for the combustion of one kg of paddy straw biomass was computed as 6.37corresponding to internal combustor volume of 5.2 m^3 of air per kg of fuel. Equivalence ratio (ø) and percentage excess ratio (*n*) were computed as 0.722 and 38.4%, respectively. Total heat available from combustion of four paddy straw bales (total weight 12 kg) during 30 min. period was calculated to be 153 MJ. Heat generated by the paddy straw bale in 3 min. is 15.3 MJ. Heat gained by water to boil in 3 min. was 5.08 MJ *i.e.* 33.2% of heat generated by combustion of the paddy straw. If, heat loss from the surface of the furnace is considered between 8-10%, even then about 60% of the heat is left with the flue gases which can be used for other useful heating applications.

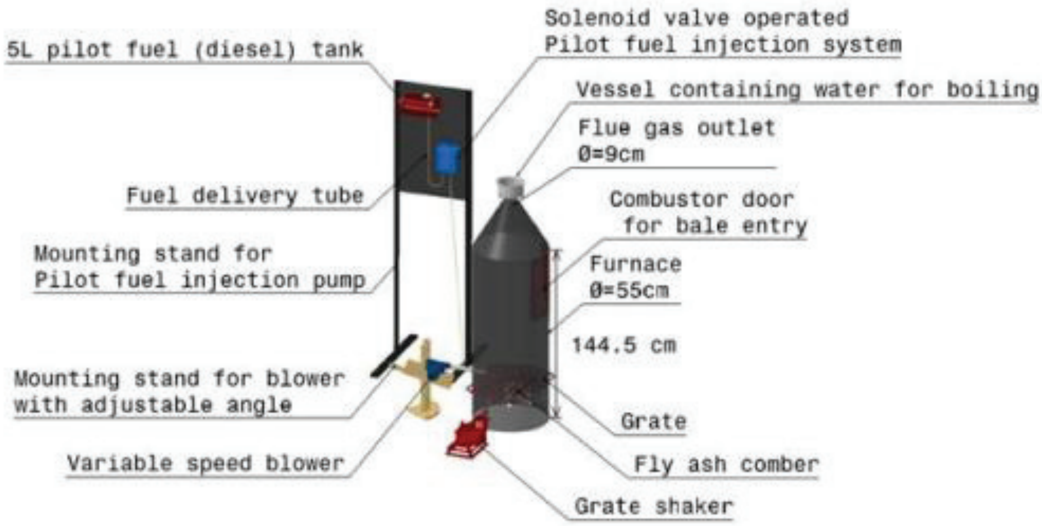

Fig.1. Isometric view of the solid model of the paddy straw biomass combustor prototype

Flue gas temperature profile

Flue gas temperature at the outlet of combustor just below the water container was measured between 329 and 354°C during 30 min. trial run during which, 4 paddy straw bales of 3 kg weight were burnt with just around 8-10 ml of pilot fuel. Initially, the flue gas temperature was equal to the ambient air temperature of 33°C. The temperature of the flue gas before making contact with the vessel (Tflue) began to increase rapidly after manual ignition of the biomass. After about 3min., when the 1st spray of the pilot fuel occurred, the flue gas temperature increased sharply and reached about 280°C; when the 2nd spray of fuel occurred (after 6min.) further improvement in burning and flue gas temperature (exceeded 350°C) were noticed as shown in Fig. 3.

Fig.2.(a) Experimental set up for testing of bale combustor and (b) boiling performance test of bale combustor

It was further observed that at the point, when the 1st bale was nearly burnt, Tflue began to drop slightly reaching 325°C. The 2nd bale was introduced

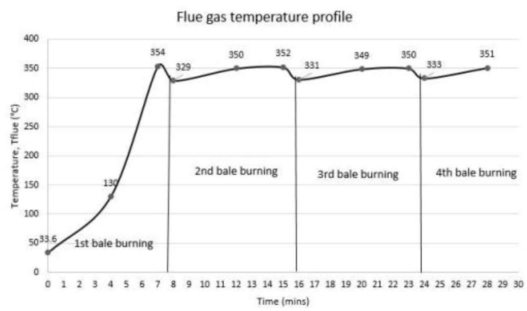

Fig.3. Temperature profile of flue gas for trial run of prototype design of bale combustor with pilot fuel injection system

at the start of 8th min. which caught fire immediately along with the previous flame after 9th min. With the 3rd spray of pilot fuel, Tflue again increased to 350°C and remained almost stable till 15th min. As soon as the flue gas temperature started to drop 3rd bale was introduced. The 5th spray again caused the flue gas temperature to reach close to 350°C. The 4th and the last bale was introduced before the beginning of the 24th min., which caused Tflue to reach 351°C just after the 8th spray of fuel. It is pertinent to note that from the start of trial to 7th min, Tflue rise was in transient state. When steady state was almost achieved after the 2nd bale loading (between 11th to 15th min.), a container with 2 L water was placed above the outlet of cone, so that flue gases at about 350°C came in contact with the water.

Vessel water temperature

Temperature of 2 L water in the vessel increased linearly from 33ºC in the beginning to its boiling point (99.6ºC) after 3 min. at an average flue gas temperature of 350°C as shown in Fig. 4. The boiling water was used to make 8 cups of dip tea and was served to all present in the laboratory. There was almost a linear rise in the water temperature due to almost constant temperature of flue gas source temperature, indicating that any fluctuations in the flue gas temperature profile were taken care by the pilot fuel supply thus, making it stable for the period when the sufficient unburnt biomass was available in the combustor.

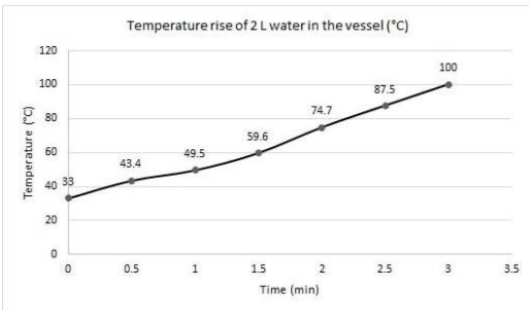

Fig.4. Temperature rise curve for 2.1. water up to boiling on the prototype design of bale combustor

Paddy straw management potential for useful heating

In Punjab, about 16mT paddy straw is burnt in the fields every year (Singh *et al.,* 2008) causing a lot of pollution and health issues. This heat can be put to alternate use for year-round water heating and room heating in winter. Experiments have shown that the developed paddy straw biomass combustor for domestic use is capable of heating 40 L of water per hour by utilizing 25 kg of paddy straw biomass. For 10 h of daily operation, 250 kg of paddy straw and 120 ml of pilot fuel costing Rs.12 only are required as compared to electricity cost of 2kW geyser operating for 10 h per day accumulating a total cost of about Rs.120.

Conclusion

A prototype design forced draft paddy straw biomass combustor with an innovative pilot fuel injection system and grate shaker was developed and tested, which showed that mixing of pilot fuel intermittently with blower air helped in flame sustainability for achieving the complete combustion and flue gas temperature could rise up to 350°C. Two litres of water can be heated up to boiling point within 3min., which shows that the designed combustor has the potential to heat 40 L of water per hour by utilizing about 250 kg of paddy straw and120 mL of pilot fuel. Compared to electric geyser to heat the same quantity of water, the proposed combustor is about 10 times cheaper with respect to operating cost.

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