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An investigation in 20 kW_{th} oxygen-enriched bubbling fluidized bed combustor using coal and biomass

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ABSTRACT

The current article presents the experimental finding of co-firing coal with biomass under air-fired and oxygen-enriched conditions in a 20 kW bubbling fluidized bed (BFB). For the same, rice husk (RH), *Prosopis juliflora* (PJ), pine needles (PN) and plant litter (PL) are used as biomass alongside the coal. The bounteous accessibility of biomass in Northern region of India is the primary explanations behind its choice. The best possible usage of these biomass can possibly fortify the economy and additionally decreases the pollution. The experimental results show that the coal-biomass blend burns successfully inside the combustor, and the maximum temperature observed in the splash zone. A maximum conceivable combustion efficiency of 97.09% is accomplished with 75%coal/25%PJ under oxygen-enriched condition. The measured percentage of NO_x, CO_2 and other gasses is highly influenced by oxygen intake. The energy consumption, exergy destruction, and exergy efficiency are also assessed for fuels used. Exergy efficiency is varying from 30% to 58% for all the cases. The effect of particle size distribution on combustion efficiency is additionally studied. Among the four biomass fuels tested, PJ and PN have the best execution in co-firing mode.

1. Introduction

Fluidized beds are mostly preferred due to their excellent thermal and mixing properties [1] whereas, oxygen-enriched (air enriched with oxygen, O_2/N_2 mode) and oxy-combustion (O_2/CO_2 mode and O2/RFG mode) fluidized beds are the latest technologies proposed by many researchers to provide clean energy. India, being a developing country has an enormous demand for the clean energy to meet the future requirements. As an objective to provide the electricity access to each individual in the nation, fuel security and healthy environment, it is essential to investigate the renewable energy resources. Biomass like agricultural waste, organic matter, forest waste, and so on are available bounteously within the nation.

Co-firing of coal with biomass can be an attractive approach to increase the share of renewable energy resource and reduce the dependency on fossil fuel that further contributes to the sustainability of the natural resources [2]. Co-firing biomass with coal either in oxygen-enriched or oxy-combustion fluidized bed provides the dual benefits; the first benefit of biomass is as a renewable energy resource and secondly it provides the most favorable environments for the combustion of solid fuels. It has a potential for negative CO_2 emission level for power generation [3,4] as biomass combustion is considered to zero greenhouse emission in air firing mode. Jia et al. [5,6], Krzywański et al. [7], Guedea et al. [8] and Czakiert et al. [9] investigated the fluidized bed combustor under oxygen-enriched and oxy-combustion conditions experimentally, where the artificial neural network (ANN) approach is introduced for the same conditions by Krzywanski et al. [10–12], which may overcome the shortcomings of experimental procedures. However, oxygen-enriched or oxy-combustion technology is still not applied commercially for CO_2 capture [13]. Few author examined the biomass as a fuel instead of coal (Singh et al. [14] agro-residues, Singh et al. [15] rice husk, Tzamtzis et al. [16] pine needles, Font et al. [17] pine needles and cones, Krzywanski et al. [18,19] forest biomass, sunflower husk, and willow), but co-firing in fluidized bed for oxy-enriched or oxy-combustion conditions is not explored much. The behavior of many fuels is not understood for such conditions.

Pine needles are sort of biomass which are abundantly available in the North, India. Approximately 1500 square km pine forest is available in the state Himachal Pradesh, India and 3400 square km in the state Uttrakhand, India. As per the report [20] presented by the Ministry of New and Renewable Energy, Government of India in 2012, 1 m^2 of pine forest will yield 1.19 kg of pine needles every year and a 100 kW gasifier running for 24 h would require 4500 kg of pine needles. Highly inflammable and non-biodegradable pine needles are spread over the forest floor area that catches fire instantly in the summer due to high atmospheric temperature. The forest fire produced a higher gas emission and considerable damage to the economy and biodiversity. It is necessary to utilize these pine needles to make some valuable product, and one solution is to harness the energy from the same. *Prosopis juliflora*

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Nomenclature

$F(\phi)$	mass fraction
$f(\phi)$	density function
h_a	specific enthalpy of the air (kJ/kg)
h_f	specific enthalpy of the fuel (kJ/kg)
h_P	specific enthalpy of the hot product (kJ/kg)
h_O	specific enthalpy of the oxygen (kJ/kg)
I_C	exergy destruction (kJ/h)
k_S	Siegert constant
l	mean particle size (mm)
m	measure of the spread of particle sizes
$\dot{m}_a$	mass flow rate of air (kg/h)
$\dot{m}_f$	mass flow rate of fuel (kg/h)
$\dot{m}_o$	mass flow rate of oxygen (kg/h)
$\dot{m}_p$	mass flow rate of flue gas product (kg/h)
S_L	flue losses
T_{fg}	flue gas temperature (°C)
T_a	ambient air temperature (°C)

Greek letters

ε_a	exergy of air
ε_f	exergy of fuel
ε_O	exergy of oxygen and combustion products
ε_P	exergy of combustion products
ϕ	particle size (mm)
ψ	exergy efficiency (%)

Acronyms

AF	air-fired
BFB	bubbling fluidized bed
HHV	higher heating value (MJ/kg)
LHV	lower heating value (MJ/kg)
PJ	*Prosopis juliflora*
PL	plant litter
PN	pine needles
PSD	particle size distribution
OE	oxygen-enriched
RH	rice husk
RR	Rosin Rammler
TGA	thermogravimetric analysis

is one of the major biomass consumed by biomass power plants in Rajasthan, India. As per the report [21] of "Rajasthan Renewable Energy Corporation Limited India, 2015," approximately 29.3 megaton *P. juliflora* is generated per year. Out of which 25.8 megatons/year was consumed for domestic fuel, local bakery, hotel industries, biomass power plant and another local thermal energy consuming industries, the remaining 3.5 megatons/year was considered as surplus quantity. This fuel is available throughout the year and used as biomass power plant. As fluidized bed has the capability to burn fuel directly, so there is no compelling reason to make the bricklet of PJ and PN.

The primary aim of this work is to investigate the combustion/emission characteristics and performance of co-firing coal with biomass (pine needles (PN), *P. juliflora* (PJ), plant litter (PL) and rice husk (RH)) in an oxygen-enriched bubbling fluidized bed. Observations are made for combustion efficiency, temperature profile, flue gas emission, energy consumption, exergy destruction and exergy efficiency of combustor by using a different blend of the co-firing coal with biomass. Therefore, the current work is a concern with the burning of different fuels and their blends under oxygen-enriched conditions.

2. Literature review

Co-firing in a fluidized bed with the oxygen-enriched or oxy-combustion condition can possibly enhance fuel burnout and reduce the emission level. Few authors [21–33] demonstrated the miscellaneous type of studies for such conditions. The particle characterization under these conditions is a concern of maximum of studies. Table 1 summarized the feasibility or finding of the different setups used by the researchers for the co-firing under oxygen-enriched or oxy-combustion conditions. It is observed from the literature that few biomass fuels are verified under a limited oxygen range of 21% to 40%.

3. Materials and methods

3.1. Details of experimental setup

The work described in this paper was performed on a lab scale oxygen-enriched bubbling fluidized bed combustor having two cyclones (C1 and C2), induced fan, flue gas cooler and stack. This setup is designed for high ash coal and biomass hence; two cyclones used. Fig. 1 shows the schematic diagram of the experimental setup and Fig. 2 shows the photographic view of the oxygen-enriched BFB.

The detailed description of the setup is given in Table 2. The BFB has been allowed to the fluidization with air or oxygen. The oxygen can supply from the bottom through a distributor as well from the side through the freeboard. The combustor is insulated with a ceramic fiber board from the inner side and with glass wool from the outer side to reduce the heat losses. The net thermal capacity of this system is below 20 kW. For the delivery of the coal, biomass or their premixed blend into the combustor, a motor driven screw feeder with storage hopper is installed. The fuel is entering into the splash zone, above the combustor bed and a stepper motor is used to control the feed rate by varying the rotational speed of the motor. The maximum amount of the solid fuel supplied to the combustor is 20 kg/h. The pressure measurement has been done in cold conditions due to unavailability of instrument that could measure pressure at a high temperature in the lab. Initially, the bed is heated by four electric heaters mounted in the bed above distributor. Combustion was initiated with the help of liquified petroleum gas (LPG). Air and oxygen are introduced as primary air or O_2 through the distributor nozzle in the bed and as secondary air or O_2 through the nozzle in the freeboard as shown in Fig. 1. No foreign bed material was used for fluidized-bed combustion; ash generated itself works as a bed material.

3.2. Temperature and gas emission measurements

When steady state is reached, the temperature of bed, splash zone, and freeboard is measured at different heights along the fluidized bed combustor for each test. Gas concentrations [i.e. O_2, CO, CO_2, NO_x, SO_2] for each test are monitored above the freeboard and in the chimney by employing a "testo 350" professional portable flue gas analyzer. The instrument consists of the control unit and measuring instrument. Readings are taken by directly entering the flue gas probe in the freeboard.

3.3. Particle size distribution

The particle size of the fuels significantly affects the burning, a smaller size fuel particle tends to create faster ignition then the larger particle. Particle size distribution (PSD) of various types of biomass used has been studied by applying the Rosin–Rammler (RR model) method for obtaining distribution function $F(\phi)$ (mass fraction) and density function $f(\phi)$ (number of particles binned between