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Co-combustion of biomass and gaseous fuel in a novel configuration of fluidized bed: Thermal characteristics

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ABSTRACT

Experimental study on co-combustion of rice straw and natural gas has been performed in a fluidized bed. The used combustor allows the novel, jetting-fountain configuration and the conventional operation as well. In the jetting-fountain configuration, natural gas premixed with the air sufficient for combustion proceeds through the jet pipe to create a jetting-fountain zone. Whereas only the air required for rice straw combustion passes through the gas distributor. The experiments show that smooth combustion of natural gas with rice straw can be performed in the jetting-fountain fluidized bed avoiding acoustic effects and explosions of burning bubbles that occurs in conventional operation. The jetting-fountain fluidized bed is shown to dampen greatly the freeboard overheating at particularly lower bed temperatures. This is because the fountain-particles absorb a great part of heat released in the freeboard and recover it back to the bed. It is confirmed by measuring the in-bed cooling load that was found to increase considerably at lower bed temperatures. The natural gas contribution is found to play a major role when applying the jetting-fountain configuration. Increasing the natural gas contribution enlarges the fountain zone that causes greater reduction in the freeboard overheating and recovers more heat back to the bed. Measuring the in-bed cooling also approves the later conclusion.

1. Introduction

Biomass is recognized as a potential energy resource to mitigate emission greenhouse gases [1–9]. Utilization of biomass energy at large scale could contribute to sustainable development on different fronts including, environmental, social, and economical [4,5,10]. Biomass is renewable and nearly CO_2-neutral fuel when managed in a sustainable manner [7,11]. Moreover, using biomass for energy production assists to solve the waste disposal problem and avoids landfilling materials that ultimately decompose forming both CO_2 and methane, more harmful greenhouse gas [12]. Nowadays biomass contributes about 10-15% of the total world energy demand [1,10,13].

Co-combustion with fossil fuels promotes the use of biomass and provides one alternative to achieve emission reductions. Among the other renewable energy options, co-combustion is the lowest risk, least expensive and most efficient [14,15]. Adding biomass to a coal-fired boiler has no or slightly impact on the overall generation efficiency of a coal fired power plant [16]. Co-combustion of biomass and coal has been subjected to intensive studies that used essentially every major type of biomass (herbaceous, woody, animal wastes, and anthropomorphic wastes) combined with different ranks of coal [17–26]. Contribution of biomass mainly reduces CO_2 emissions. Further, Co-combustion of biomass with fossil fuels provides means to reduce SO_2, and it also may reduce NO_x emissions [26–33].

Open burning of rice straw is a serious problem in Egypt where smoke cloud is easily detected during the harvest season. Burning of rice straw in the field releases pollutants that contribute to greenhouse gases without energy gain. Utilization of rice straw and rice husk in energy production is a promising option. Combustion of rice by-products in fluidized bed has been carried out in different works [34–39]. Many other works have been successfully performed on co-combustion with coal [40–44] or bitumen [45–47].

The combustion of gaseous fuels in fluidized beds is characterized by acoustic effects and explosion risk [48,49] and post-combustion is significant in the freeboard particularly at lower bed temperatures [48–56]. Post-combustion has been also found important in the combustion of biomass [34,57,58] and liquid fuels [59–61]. The ejected bed particles in the splashing zone absorb a part of the heat released in the freeboard and recover it back to the bed. These particles also act as a heat sink that contributes to controlling the freeboard temperature [46,58]. Moreover, other studies indicated

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that the contact between gas and solids is very poor in the main bed while it is very good in the splashing zone [62,63].

In this work co-combustion of rice straw and natural gas in fluidized bed has been investigated. The novel fluidized-bed configuration, namely the jetting-fountain configuration, developed by Okasha [64–67] has been applied to avoid the shortcomings discussed above. The jetting-fountain configuration enables gaseous fuels to burn smoothly similar to a normal premixed flame avoiding acoustic effects and explosions risk. It enables a rapid and reliable method for initial heating of fluidized-bed reactor and reduces considerably the power consumed in feeding gases to the combustor. Applying the jetting-fountain to co-combustion of rice straw and natural gas has been carried out. The post combustion and overheating in the freeboard have been examined at different conditions by measuring the axial temperature distributions. The impact on the heat gain by bed has been explored by assessing the in-bed cooling load. Influence of fuels blending ratio on thermal characteristics has been studied. Effect of bed temperature has been also considered. Table 1 gives a comparison between the current work and our previous works.

2. Experimental

2.1. Apparatus and technique

The apparatus used in this work is a bubbling fluidized-bed combustor that has been modified to adopt the jetting-fountain configuration as shown in Fig. 1. It has a fluidization column of 300 mm ID and 3300 mm height. The fluidization gases are distributed using a nozzle-type plate. A stainless steel tube of 38.1 mm ID passes through the center lines of the gas distributor plate to the centerline of the fluidization column to feed jet-gases vertically upward. In order to adjust the location of the jet with respect to the bed surface, the tube is designed to be movable in the vertical direction.

The combustor allows the conventional operation and the novel jetting-fountain configuration. In conventional operation, all air is pre-mixed with natural gas and delivered through the gas distributor. In the jetting-fountain configuration, on the other hand, only the air required for rice straw combustion passes through the gas distributor as shown in Fig. 2. Natural gas premixed with sufficient air proceeds through the jet pipe to create a jetting-fountain zone. The jetting-fountain configuration enables a rapid and reliable method for initial heating of the fluidized bed reactor [65]. The flow rates of natural gas and air are measured with rotameters. The measuring errors of used ranges are within 3% for natural gas and within 2% for air.

The combustor is equipped with a continuous over-bed fuel feeding system using a calibrated paddle shaft driven by a variable speed electric motor. Downstream the paddle shaft, a screw feeder is used to drive the rice-straw pellets through an inclined pipe flanged with the combustor at 1500 mm above the air distributor. The evaluated error of feeding system is within 7% of mass feed rate. The combustor also contains a heat exchanger system which

Table 1
Current work in comparison with our previous work.

Combustor	Ref.	Method	Fuel and operation	Major outcomes
Fluidized bed 300 mm ID	[34]	Firing tests	Rice straw pellets and staged air combustion	• Staged air is an effective technique to reduce NOx, in particular, at higher operating temperature • Secondary air ratio of 20–25% appears an optimum range for the combustion performance
	[45]	Co-firing Tests	Straw-bitumen pellets and batch tests	• Pellets of rice straw and bitumen are attractive as an alternative fuel being characterized by a relatively high efficiency, moderate NOx, "intrinsic" sorbent capability plied by ashes of rice straw
	[46]	Modeling and Co-firing tests	Straw-bitumen pellets and continuous operation	• The model furnishes an axial temperature profile for the splashing and freeboard zones which is characterized by two maxima. • Overheating in the freeboard zone may be controlled by adjusting operating parameters
	[60]	Firing tests	Heavy liquid fuel (Mazut) & continuous operation	• Mazut steady state combustion is realized in fluidized bed with high combustion efficiency up to 99.8% • Sulfur retention up to 91% has been achieved by adding limestone
	[61]	Modeling and firing tests	Liquid fuels and continuous operation	• A new approach is proposed to account for gas mixing due to bubbles coalescence and an equivalent mass interchange coefficient has been derived • Gas mixing is the rate limiting step for the in-bed combustion processes and good liquid fuel distribution over the bed cross-section is the most important factor to have efficient in-bed combustion
Fluidized bed 100 mm ID & FB 300 mm ID	[47]	Co-firing tests	Straw-bitumen pellets with CaO built-in and batch + continuous operation	• Building-in CaO is a very efficient technique for retaining sulfur • Building-in sorbent technique could greatly reduce the quantity of used sorbent. This, in turn, might result in more economic sorbent utilization
Jetting-fountain fluidized bed 300 mm ID	[65]	Cold tests and firing tests	Gaseous fuel and continuous operation	• Jet-fountain fluidized bed configuration enables gaseous fuels to burn smoothly avoiding acoustic effects and explosions due to volume combustion in bubble phase • The novel configuration reduces greatly the power required to feed gases into the combustor
	[66]	Firing tests	Propane and continuous operation with staged-air combustion	• A rapid reliable method for initial heating of fluidized bed combustor has been confirmed • The novel configuration is more effective in reducing NOx. CO doesn't exhibit a significant change with increasing secondary air applying the novel configuration while it multiplies in the case of conventional operation
	This work	Co-firing tests	Natural gas + biomass and continuous operation	• Co-firing with jetting-fountain configuration dampens greatly the freeboard overheating at particularly lower bed temperatures • The in-bed cooling load increases greatly at lower bed temperatures when applying jetting fountain configuration with higher natural gas contribution