BIOMASS AND BIOENERGY 79 (2015) 105–115

Available online at www.sciencedirect.com

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Combustion, cofiring and emissions characteristics of torrefied biomass in a drop tube reactor

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A R T I C L E I N F O

Article history:
Received 4 July 2014
Received in revised form
11 May 2015
Accepted 13 May 2015
Available online 27 May 2015

Keywords:
Torrefaction
Biomass
Cocombustion
Cofiring
Combustion

A B S T R A C T

The study investigates cofiring characteristics of torrefied biomass fuels at 50% thermal shares with coals and 100% combustion cases. Experiments were carried out in a 20 kW, electrically heated, drop-tube reactor. Fuels used include a range of torrefied biomass fuels, non-thermally treated white wood pellets, a high volatile bituminous coal and a lignite coal. The reactor was maintained at 1200 °C while the overall stoichiometric ratio was kept constant at 1.15 for all combustion cases. Measurements were performed to evaluate combustion reactivity, emissions and burn-out.

Torrefied biomass fuels in comparison to non-thermally treated wood contain a lower amount of volatiles. For the tests performed at a similar particle size distribution, the reduced volatile content did not impact combustion reactivity significantly. Delay in combustion was only observed for test fuel with a lower amount of fine particles. The particle size distribution of the pulverised grinds therefore impacts combustion reactivity more.

Sulphur and nitrogen contents of woody biomass fuels are low. Blending woody biomass with coal lowers the emissions of SO_2 mainly as a result of dilution. NO_X emissions have a more complex dependency on the nitrogen content. Factors such as volatile content of the fuels, fuel type, furnace and burner configurations also impact the final NO_X emissions. In comparison to unstaged combustion, the nitrogen conversion to NO_X declined from 34% to 9% for air-staged co-combustion of torrefied biomass and hard coal. For the air-staged mono-combustion cases, nitrogen conversion to NO_X declined from between 42% and 48% to about 10%–14%.

1. Introduction

Across Europe, a combination of incentives and policy directives by national governments has enabled considerable progress towards fulfillment of the EU set targets of obtaining 20% of Europe's total primary energy consumption from renewable sources by the year 2020. Greenhouse gas emissions in 2013 were 19% lower than 1990 levels in Europe. They are expected to be 24% lower by 2020 on the basis of current policies. The share of renewable energy has increased to 14% in 2012 as a proportion of final energy consumed and it is expected to rise further to 21% in 2020 [1]. Biomass fuels can play an increasing role in the renewable energy mix. In spite of

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http://dx.doi.org/10.1016/j.biombioe.2015.05.010

the difficulties in the current investment climate due to political uncertainties concerning the utilization of biomass fuels in power plants, cofiring of torrefied biomass fuels can be a reliable option. The properties of torrefied biomass fuels make it's handling similar to coals in many ways and this presents the possibility for coal fired power plants to reduce their carbon intensity with less capital expenditure on new infrastructure [2]. This is in addition to reduction in emissions of SO_X and NO_X when cofiring torrefied biomass fuels.

Cofiring biomass is technically proven and it can reduce the carbon intensity of coal-fired power plants. Cofiring shares in conventional pulverized coal fired power plants have increased from about 1 to 10% based on energy input, to over 20% over the past decade. In some pulverized coal fired installations, a complete switch from coal to biomass has been demonstrated [2].

Utilization of biomass fuels in pulverised fuel boilers presents challenges due to biomass properties such as high moisture content, low volumetric energy density, hydrophilic nature and high bulk volume which make it expensive to transport, handle and store. Additionally, the fibrous and tenacious nature of biomass makes it difficult to mill and cofire in already existing pulverized coal milling and firing systems. Other problems such as slagging and fouling related to biomass use are connected to significant amount of alkali metal (i.e potassium) present in biomass ash. These drawbacks hence necessitated the development of biomass pretreatment technologies to improve the quality of biomass as a solid fuel substitute for coal.

Hydrochemical treatment, torrefaction, hydrothermal carbonization (HTC) and steam explosion are examples of some techniques for biomass pre-treatment. These pretreatment methods have their benefits and address different properties of biomass. Torrefaction process involves the heating of biomass in the absence of O_2 to a temperature of 200 °C–320 °C thereby reducing the moisture and volatile content of biomass. The torrefaction process has the advantage that it can be operated at high process energy efficiency; typically 96% thermal efficiency and 92% net process efficiency (including the internal electricity consumption) [3,4].

During torrefaction, the hemi-cellulose fraction which is responsible for the fibrous structure is weakened resulting to improved grindability [5–7], making it possible for torrefied biomass to be co-milled or milled in already existing pulverized coal-firing facilities, without much alteration. This implies cost savings on capital expenditure for new and sometimes expensive infrastructure. Transportation costs are reduced due to higher energy density of torrefied biomass, which is similar to the energy density of some coals [7]. The hydrophobicity of torrefied biomass is also improved as a result of destruction of the hydroxyl (–OH) groups, causing the biomass to lose its capacity to form hydrogen bonds. Handling and storage cost savings can be made here due to lower moisture uptake which in addition extends the shelf life of torrefied biomass pellets [8].

During combustion, biomass first loses moisture and then volatile gases depending on the heating rates in the process of devolatilization. Moisture, CO, CH_4 and other gaseous components are released in the process. This is then followed by a slower oxidation of the left over solid residue (char) leaving ash behind [9–11]. Pulverised biomass fuels for combustion in pulverized fuel facilities have larger and more irregular particle sizes in comparison to coal but biomass fuels are also characterized by a larger volatile fraction. This partly compensates for the coarser particles and is important for ignition, particle heat-up and consequently carbon burnout. The kinetics of biomass devolatilzation and char combustion has been extensively studied [9–11] and biomass cofiring in conventional power plants has increased to over 20% while 100% demonstration tests have already been performed [2].

Torrefied biomass fuels are characterised by higher fixed carbon and lower volatile fractions in comparison to non-thermally treated biomass. The combustion kinetics is beginning to receive increasing research interest but there is a limited amount of published experimental data available. Published data available on the devolatilization and char combustion indicate lower volatile yields as well as lower reactivity of torrefied biomass char in comparison to non-treated biomass chars at high heating rates [12,13]. Char combustion is the slower combustion process and it impacts combustor and boiler design. The experimental work aims to evaluate any such differences in combustion behaviour between torrefied biomass and non-thermally treated wood at high temperatures in a drop tube furnace. The cofiring characteristic with brown and hard coals form part of the aims of the experimental work.

Sulphur content of woody biomass is lower compared to coals. Blending woody biomass with coal lowers SO_X emissions mainly as a result of dilution [14]. NO_X emissions have a much more complex dependency on the nitrogen content. Factors such as volatile content of the fuels, fuel type, furnace and burner configurations also impact the final NO_X emissions. Due to the lower nitrogen contents, it is also possible to reach lower emissions. In pulverized solid fuel combustion systems, fuel nitrogen conversion is the major pathway to emissions of NO_X rather than Zeldovich (thermal NO_X) or prompt NO_X mechanisms [15]. Air-staged combustion is considered one of the most efficient existing technologies for reducing NO_X emissions and it has been the most widely accepted technology in coal-fired power plants. The study also aims to explore the potential for reducing NO_X by air-staging during torrefied biomass combustion and co-combustion.

2. Materials and methods

2.1. *Test facility*

Experiments were carried out in IFK's entrained flow, drop tube reactor, BTS-VR (20 kW), shown in Fig. 1. It consists of a ceramic tube reaction zone of 2500 mm length and 200 mm diameter which is electrically heated at five zones, T1 to T5 and embossed to maintain a constant wall temperature (up to 1400 °C). The pulverized fuel stream is dosed from a coal screw feeder into the reactor by means of carrier air through the central tube of the top-mounted circular jet burner. Biomass and coal were pre-mixed during the cofiring cases. Char and flue gas samples were extracted at various distances from the burner along the axis of the vertical down-fired reactor. The flue gas is transported via an electrically heated tube, an