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Emission characteristics of co-combustion of a low calorie and high sulfur–lignite coal and woodchips in a circulating fluidized bed combustor: Part 1. Effect of excess air ratio

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HIGHLIGHTS

- Increasing excess air lowered temperature but mixing in the combustor was improved.
- With the addition of woodchips, combustion shifted to the upper part of the riser.
- Addition of woodchips increased CO emission, reduced char formation and NO emission.
- Optimum excess air ratio increased with addition of woodchips to fuel mixture.

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ABSTRACT

In this study, co-combustion of Bursa–Orhaneli lignite and woodchips mixtures containing 10%, 30% and 50% by wt. of woodchips was studied in a circulating fluidized bed combustor in order to investigate the effect of excess air ratio (λ) on the flue gas emissions. The combustor has an inside diameter of 108 mm and a height of 6 m. The temperature of the combustor is kept at 850 °C during the combustion tests. During the combustion tests, CO, O_2, NO, and SO_2 emissions in the flue gas was continuously measured and recorded by ABB-AO 2000 flue gas analyzer.

The results of the tests showed that increasing excess air had a cooling effect on the combustor, but at the same time it also provided smoother temperature profile along the combustor. In order to get minimum flue gas emissions, the optimum excess air ratios for the co-combustion tests of fuel mixture including 10%, 30% and 50% by wt. of woodchips were determined to be 1.18, 1.32 and 1.41, respectively. While woodchips addition to the lignite made CO emissions worse, it did not change NO emission. CO and NO emissions were below the limits but SO_2 emission was above the limit for the case of 10% and 30% woodchips co-combustion at optimum excess air ratio. In the case of 50% woodchips co-combustion, SO_2 and NO emissions were under the limits but CO emission was a little above the limit at optimum excess air ratio.

1. Introduction

World total primary energy supply (TPES) has been doubled in last 40 years due to the increase in human population and energy-based life-style. While it was about 6 Giga tonnes of oil equivalent (Gtoe) in 1973, it increased to about 12 Gtoe in 2010 [1]. Turkey's TPES in 2011 was 114 Million tonnes of oil equivalent (Mtoe) and 72% of it was met by imports [2]. The high percentage of imports is not desirable for sustainable economic development. Therefore, it is highly important to use indigenous energy resources in energy production in Turkey.

Turkey is rich in coal reserves and it is among the twelve biggest coal producers in the world with a production of 78.1 Million tonnes (Mt) in 2011. 95% of this production is lignite coals. In 2011, Turkey was the fourth biggest lignite producer following Germany, China and Russia [3]. In addition to lignite reserves, Turkey also has a high production potential of biowastes. Biomass energy potential of Turkey is estimated as 32 Mtoe [4,5] and the total recoverable potential was estimated to be about 16.9 Mtoe [5–7]. Among the biomass resources, forestry residues has become more important

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because of both high production potential of the residues and also the necessity of the residues to be removed from forests in order to prevent forest fires and to regenerate the forest areas. The temperature changes due to global warming were reported as the main reason for the forest fires, with hotter years producing more fires [8]. General Directorate of Renewable Energy of Turkey recently estimates the biomass potential of forestry wastes to be 4.8 Mt which is equivalent to 1.5 Mtoe [9]. It would be beneficial to use forestry residues in energy production to minimize the foreign-source dependency as well as for sustainable forest management. Additionally, Turkey, under the umbrella of FOREST EUROPE (The Ministerial Conference on the Protection of Forests in Europe), commits to use woody biomass as renewable energy source in energy production and to remove the residues from forests to reduce risk of fires according to the Warsaw Resolution 1 [10]. General Directorate of Forestry (GDF) in Turkey aims to increase the use of biomass and to reduce the share of fossil fuels in new power plants in electricity production [11].

Among the forestry residues, *Rhododendron*, which is a genus of woody plants, is an important biomass source. Acar et al. [12] noted in 2011, that 500,000 hectares of area in the Black Sea region was covered by *Rhododendron* spp. (a species of *Rhododendron* genus) and its potential as a biomass resource was estimated as 50 Million tons referring to the master plan of GDF [13]. *Rhododendron* is a fast-growing plant covering the entire land in a short period of time. Due to this property, it plays an important role in preventing soil erosion. However, regeneration of the forests becomes impossible due to this fast-growing plant. Therefore, *Rhododendron* is undesirable in the forest areas [14]. GDF removes *Rhododendron* residues (it will be mentioned as "woodchips" in the text below) from the forests due to adverse effect of them on the regeneration of trees and wants to use them in energy production.

Turkey ratified The United Nations Framework Convention on Climate Change (UNFCCC) in 2004 and The Kyoto Protocol in 2009. The total greenhouse gas emission of Turkey was calculated to be 402 Mt CO_2 equivalents in 2010 and the energy sector was responsible for 88.2% of this emission. The removal effect of the Land use, Land-use Change and Forestry (LULUCF) on greenhouse gas emissions (−78.7 Mt of CO_2 equivalent)) has been taken into effect [15]. If it is considered that the main greenhouse gas emissions were due to the energy sector in Turkey, the use of biomass resources which are defined as "CO_2 neutral" [16] in the energy sector is important for Turkey to fulfill the possible future commitments based on the Kyoto Protocol.

Additionally, the use of indigenous resources such as coal and biowastes for energy production is of critical importance in reducing energy imports. The average net heating value of Turkish lignites is about 9265 kJ/kg [3]. Among the combustion technologies, fluidized bed technology has become more important because of its ability to burn different types of fuels due to the good mixing in the combustor and the high combustion efficiency achieved with less air given into the combustor [17,18].

In the light of these needs, the potential to build power plants using coal as main fuel and various biomasses as supplementary fuel appear to be a promising choice for Turkey. Thus, the disposal of biowastes will be achieved and the energy content of the biowastes will be used beneficially in the country's energy production. Additionally, CO_2 emission will be reduced which will provide the opportunity for a carbon credit. There are many studies in the literature about the investigation of biomass combustion [19–24] as well as co-combustion of coal with various biomasses [25–37] in fluidized bed combustors. However, there is no study on the co-combustion of biomass with Turkish lignites in circulating fluidized bed (CFB) combustors. Skrifvars et al. [38] investigated the ash characterization of combustion coal, peat and wood in terms of agglomeration and fouling in a 12 MW_{th} CFB boiler at Chalmers University of Technology, Sweden. However, while they produced important findings regarding the fate of alkalis coming from wood ash, they did not look at the co-combustion of these fuels. Lyngfelt and Leckner [39] studied specifically the effect of secondary air injection on NO emission in the cyclone outlet for the combustion of woodchips in the same unit where the study of Skrifvars et al. [38] was conducted. They reported a reduction in NO emission. Another study from Lind et al. [40] was also related with the ash behavior of two woody biomasses, forest residue and willow, during the combustion in a 35 MW CFB cogeneration plant. These studies were mainly focused on the combustion of woody biomass. Amand and Leckner [41] studied the co-combustion of sewage sludge with coal or wood in the Chalmers 12 MW_{th} CFB boiler. The study aimed to investigate the trace metal emissions from the co-combustion tests in order to see the effect of sludge share in the fuel mixture on the fate of trace metals. Co-combustion of wood and coal was not covered in the study. Gayan et al. [42] studied the co-combustion of a forest residue (pine bark from Finland) with two coals (South-African sub-bituminous coal from a power plant in Finland and a high-sulfur lignite from Spain) in two CFB pilot plants (0.1 MW_{th} (VTT, Finland) and 0.3 MW_{th} (CIEMAT, Spain)). The share of woody biomass on the carbon combustion efficiency was studied and a model was developed to predict the carbon combustion efficiency and the gas concentrations along the combustor. However, O_2 concentration along the combustor was only given according to the model; other gases (CO, SO_2 or NO) were not presented. Nevalainen et al. [43] studied the combustion of coal, woodchips and their mixtures in a 50 kW CFB reactor (VTT) and in the Chalmers 12 MW_{th} CFB boiler. The study was about the combustion dynamics such as temperature and oxygen concentration along the combustor with respect to different process inputs. Hupa et al. [44] investigated NO formation tendency of solid fuels including different types of coal, peat, biomass and wastes in a lab-scale fluidized bed. However, they just focused on the fuel nitrogen conversion in order to build a database for NO formation. Despite the existence of the studies mentioned above, there remains a lack of knowledge about the possible synergistic effect of co-combustion of high-sulfur and high-ash lignites with woody biomasses on the major emissions (CO, NO, and SO_2) and on the ash formation in circulating fluidized bed combustors. This study aims to investigate the emission characteristics of a Turkish lignite (Bursa–Orhaneli) and woodchips during the combustion of their mixtures in a lab-scale CFB combustor. In particular, the effects of the excess air ratio on flue gas emissions were examined in detail and the emission measurements were compared to the limit values in the Turkish regulation [45] and Directive 2001/08/EC of the European Parliament and of the Council of 23 October 2001 (EU Directive) [46].

2. Materials and methods

2.1. Characteristics of fuels

Bursa–Orhaneli lignite and woodchips were used in this study. "Woodchips" refers to the *Rhododendron* genus of woody plants in Ericaceae family which mainly grows in the Black Sea region of Turkey. Proximate and ultimate analyses of fuels are given in Table 1. In all combustion tests, 1–2 mm of fuel particles are used.

2.2. Laboratory-Scaled Circulating Fluidized Bed Combustor (LAB-CFBC)

The experimental setup consists of a circulating fluidized bed combustor, a fuel feeding system, electrical heaters, and two cy-