Fuel 155 (2015) 37–43

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Air staging to reduce emissions from energy crop combustion in small scale applications

J.P. Carroll [a,*], J.M. Finnan [a], F. Biedermann [c,d], T. Brunner [b,c,d], I. Obernberger [b,c,d]

[a] Teagasc, Crops Environment and Land Use Programme, Oak Park Crops Research, Carlow, Ireland
[b] BIOENERGY 2020+ GmbH, Graz, Austria
[c] BIOS Bioenergy GmbH, Graz, Austria
[d] Graz University of Technology, Institute for Process and Particle Engineering, Graz, Austria

HIGHLIGHTS

- High NO_x emissions of energy grasses can be reduced by up to 30% by air staging.
- High PM_1 emissions of energy grasses can be reduced by up to 25% by air staging.
- Optimum primary lambda for NO_x and PM_1 emission reduction was independent of fuel.
- No relationship seen between primary combustion chamber temp and emission levels.

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form 1 April 2015
Accepted 2 April 2015
Available online 11 April 2015

Keywords:
Biomass combustion
Air staging
PM_1 and NO_x emissions
Energy grasses

ABSTRACT

The results of experimental work to investigate the effects of air staging on emissions from energy crop combustion in small scale applications are presented. Five different biomass fuels (wood, willow, miscanthus, tall fescue and cocksfoot) were combusted in a small scale (35 kW) biomass boiler and three different tests looking at the effects of (1) air ratio in the primary combustion chamber (primary air ratio), (2) temperature in the primary combustion chamber, and (3) overall excess air ratio, on NO_x and particulate emissions were conducted. It was shown that by varying the primary air ratio, NO_x emission reductions of between 15% (wood) and 30% (Miscanthus) and PM_1 reductions of between 16% (cocksfoot) and 26% (wood) were possible. For all fuels, both NO_x and particulate emissions were minimised at a primary air ratio of 0.8. Particulate emissions from miscanthus increased with increasing temperature in the primary combustion chamber, NO_x emissions from Miscanthus and from willow also increased with temperature. Overall excess air ratio has no effect on emissions as no significant differences were found for any of the fuels. Emissions of particulates and oxides of nitrogen from a wide range of biomass feedstocks can be minimised by optimising the primary air ratio and by maintaining a temperature in the primary combustion chamber of approximately 900 °C.

1. Introduction

Rising energy costs, depletion of fossil fuel resources as well as efforts to mitigate the effects of climate change have all resulted in an increased interest in renewable energy, including bioenergy. Increasing demand for biomass together with limited wood supplies are forcing markets to consider non-woody forms of biomass such as agricultural crops [1]. Combustion is the most mature technology for biomass utilisation but emissions from biomass combustion are typically greater in comparison to the combustion of natural gas or light fuel oil and can contribute significantly to concentrations of particulate matter, ozone and nitrogen dioxide in ambient air [2]. A relation between air pollution and mortality has been demonstrated [3] while high ambient levels of particulate matter still have an impact on a sizable proportion of the European population particularly in urban areas [4].

Pollutant emissions from biomass combustion arise principally as a result of the chemical composition of the fuel although emissions may also be caused by incomplete combustion [5]. For example, NO_x emissions from biomass combustion mainly result

Abbreviations: NO_x, oxides of nitrogen; PM_1, particulate matter less than 1 micrometer.

* Corresponding author. Tel.: +353 599170228.
E-mail address: john.carroll@teagasc.ie (J.P. Carroll).

http://dx.doi.org/10.1016/j.fuel.2015.04.008
0016-2361/

from the nitrogen content of the fuel and NO_x emissions increase with fuel nitrogen content [1]. However, the correlation between fuel nitrogen and NO_x emissions is non-linear as the conversion of fuel nitrogen to NO_x decreases with increasing nitrogen content of the fuel. Similarly, emissions of particulate matter are directly related to the concentrations of aerosol forming elements in the fuel (K, Na, Zn, Pb) [1].

Emissions from biomass combustion may be reduced by using either primary or secondary measures [5]. Primary measures involve a modification of the combustion process whereas secondary measures take place after the combustion process. Emissions may be reduced by altering the chemical composition of the feedstock either through the use of additives or fuel blending [6–8]. Alternatively, fuel staging has been demonstrated to be an effective means of reducing NO_x emissions [9] although fuel staging is not used to any great extent in small to medium scale biomass combustion appliances. Staged air combustion is now commonly used even in small scale biomass combustion; this strategy separates combustion into a primary combustion zone where de-volatilization of the fuel takes place to produce a fuel gas which is subsequently combusted in a secondary combustion zone [5]. NO_x emissions have been found to decrease with decreasing supply of air into the primary combustion zone: primary air ratio [10–13]. Under reducing conditions in the primary combustion chamber, the nitrogen compounds formed initially from combustion (NH_3 and HCN) can be reduced to molecular nitrogen if the temperature and the residence time are sufficient [14].

Emissions of NO_x from biomass combustion have been shown to be influenced by residence time [15], combustion zone temperature [15], excess air ratio [11,13] and the use of flue gas recirculation [12]. There are conflicting reports in the literature of the influence of temperature on NO_x emissions with some studies reporting a temperature effect [15] due to faster reaction times whereas other studies have reported no effect of temperature on NO_x emissions [11]. There are also conflicting reports as to the effect of flue gas recirculation on NO_x emissions. Houshfar et al. [12] state that emissions of NO_x can be reduced by 75–80% through its use in combination with other air staging strategies. Recirculating flue gas into the combustion chamber reduces NO_x emissions by reducing the flame temperature, reducing oxygen availability and increasing residence time. Houshfar et al. [11] found that NO_x increased with total excess air ratio up to a ratio of 1.5 before decreasing until a ratio of two was reached. Skreiberg et al. [18] concluded that there was an optimum combination of primary excess air ratio, temperature and residence time for each combustion appliance which minimised the conversion of fuel nitrogen to NO_x but that primary air ratio was the key variable in reducing NO_x emission levels. Substantial reductions in NO_x emissions (up to 91%) have been reported after air staging was employed [2,13].

Reductions in particulate emissions with decreasing primary air ratio have also been reported [2,15]. Nussbaumer [2] reported that a reduction in particulate emissions in the order of a factor of five is possible by reducing primary air due to a reduction in the conversion of potassium to volatiles in an atmosphere with limited oxygen. The majority of the potassium in the fuel remains as a salt as a consequence and ends up in the grate ash fraction. Lamberg et al. [15] attributed the reduction in particulate emissions with reducing primary air supply to a decrease in the temperature of the primary combustion zone and to a consequent reduced volatilization of alkali metals in the fuel bed. Reduced secondary air supply was found to result in increased emissions of elemental carbon, organic carbon, carbon monoxide (CO), and particle numbers [15]. As the reduction in secondary air led to increased emissions, it was concluded that sufficient input of secondary air together with good mixing is important to cut down emissions.

Biedermann et al. [16] reviewed data on air staging based on experiments and experiences with nine automated boiler technologies and concluded that significant reductions in both NO_x and particulate emissions were possible if low primary air ratios are used. The review suggested, however, that only limited information on air staging was available and that air staging was applied but not optimised in many instances because of a lack of information on the correct application of air staging. Consequently, Biedermann et al. [16] concluded that the full potential of air staging as an emission reduction measure had still not been reached. Given the importance of energy crops and agricultural residues for increasing biomass use in the energy sector [1] and the fact that the full potential of air staging has still not been reached, the objective of this present study was to investigate the potential of air staging to reduce emissions from the combustion of some new, previously unstudied energy crops in small scale combustion applications. Previously, it had been suggested that the combustion of herbaceous biomass should be confined to larger combustion plants [3]. However, recent research work has shown that air staging can be successfully used to reduce emissions from the combustion of problematic fuels in small scale combustion systems [11,17]. Consequently, three air staging strategies (adjustment of primary air, adjustment of total excess air and adjustment of combustion temperature) were studied as potential means to reduce gaseous and particulate emissions from the combustion of four energy crops of relevance to Irish conditions (miscanthus, willow, tall fescue and cocksfoot) and wood.

2. Materials and methods

The experiments were conducted at Teagasc crops research centre at Oak Park near Carlow in Ireland. Five bioenergy feedstocks were used in the combustion experiments; wood, willow, miscanthus, tall fescue and cocksfoot. Wood (spruce), willow and miscanthus were combusted in chip form at 15% moisture content. For ease of combustion tall fescue and cocksfoot was pelletised into 8 mm pellets at 10% moisture content using a Jiangsu Dehui (Jiangsu Dehui Machinery & Electric Equipment Co., Ltd, Jiangsu, China) pellet mill located at University College Dublin's Lyon's Research Estate. The willow, miscanthus, tall fescue and cocksfoot were grown on the Teagasc research farm located at Oak Park Carlow. Softwood chip was purchased from a local supplier. The ash content of each fuel was conducted using the BS EN 14775:2009 standard method. The main ash forming elements (K, P, Al, Si, Mg and Ca) were measured according to EN standard 15290 using an Anton Paar Multiwave 3000 (Anton Paar GmbH, Graz, Austria) microwave digester for digestion of samples and a Perkin Elmer Analyst 400 (Perkin Elmer Ltd., Waltham, MA, USA) atomic absorption spectrometer for determination of the element concentrations. Cl and S were analysed using High Performance Liquid Chromatography (HPLC) (standard method BS EN 15289:2009).

An ETA Hack35 (ETA Heiztechnik GmbH, Hofkirchen, Austria) tilting grate biomass boiler with a rated output of 35 kW and the capability to recirculate flue gas beneath the combustion grate was used for the combustion tests. The boiler was modified so that it was possible to measure the amount of air being applied to both the primary and secondary combustion chambers. As this boiler operates using a flue gas fan to pull air through the combustion chambers, it was necessary to install flow meters in specially designed pipes (Fig. 1) which covered the air inlets and allowed for manual adjustment of the air flow. Flue gas flows (recirculated and total) were measured using a prandtl tube. Type K thermocouples were also inserted into both the primary and secondary combustion chambers to enable temperature measurements. The BilanzTH program as designed by BE2020+ was used to verify temperature measurements.