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

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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.

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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.

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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.

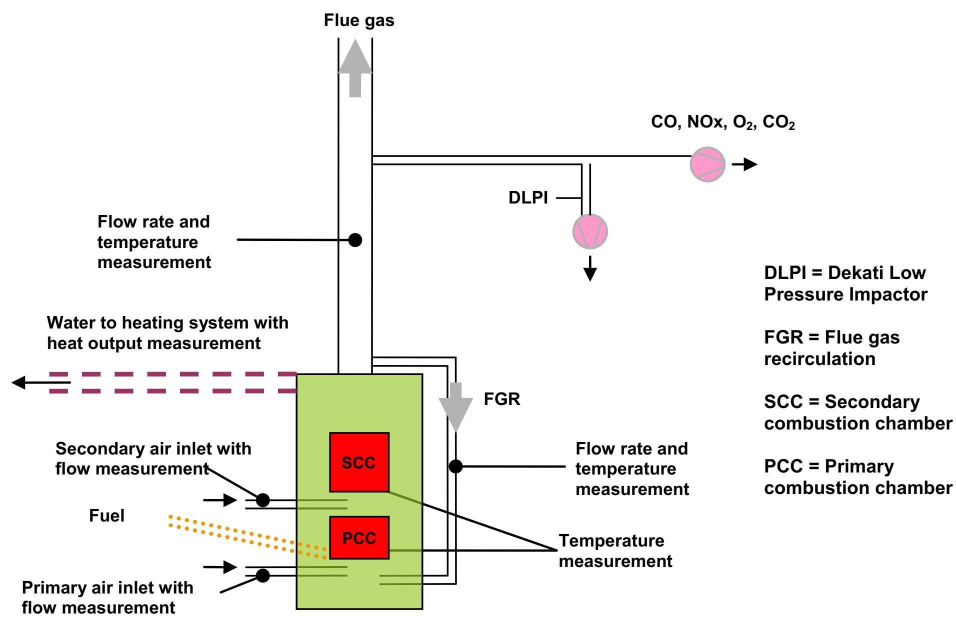

Fig. 1. Experimental set up.

Gaseous emissions were measured using a Horiba portable gas analyser (PG-250, 3880 Park Avenue Edison New Jersey NJ 08820-3097 USA) with heated sampling line. This gas analyzer uses non-dispersive IR detection for CO, SO_2, and CO_2; chemiluminescence (cross-flow modulation) for NO_x; and a galvanic cell sensor for O_2 measurements. An RS232 computer connection enabled continuous online measurements to be saved and processed.

Particulate emissions were measured using a Dekati (Tampere, Finland) 3 stage low pressure impactor with 10 μm, 2.5 μm, 1 μm and filter collection stages. This method of particulate sampling involves a known quantity of flue gas being drawn across the impactor under isokinetic conditions and the weighing of impactor plates and filter before and after testing. For this particular flue gas stream and boiler combination a 9 mm diameter nozzle was required for isokinetic sampling.

Before the research was started, a test to determine the amount of leak air entering the system was conducted using mass balances. It was found that approximately 12% leak air was entering the system, mostly through the ignition and fuel entry and the ash removal points. Any noticeable gaps were filled and as a result the leak air was reduced to approximately 7%. Prior to all combustion tests, the boiler was ignited and the temperature limited to a set value at steady state using flue gas recirculation before the commencement of tests. The amount of FGR needed to achieve the set conditions varied depending on the test being conducted, but once these conditions were reached the FGR was then held constant. It was then run for one hour in this state, during which the particulate and gaseous emissions were monitored. The fuel feed rate was kept constant and all heat produced dissipated. The experimental set up is shown in Fig. 1.

Pretest: A pretest was conducted to determine the optimum total lambda which gave the lowest CO emissions on average during combustion. Wood chips were combusted in the test setup described above under the following conditions.

- Temperature in primary combustion chamber controlled using flue gas recirculation to 1000 °C.
- Total lambda varied from 1.2 to 2.5 and the CO emissions logged.

Once determined, the optimum total lambda value was used in all subsequent tests. Three tests were conducted as follows to determine the effect of primary lambda, temperature and overall excess air ratio on emissions during the combustion of five bioenergy feedstocks.

Test 1: Varying primary air ratio: the test method as described above was employed using the following combustion conditions:

- Total lambda of 1.6 (i.e. total excess O_2 of approx. 8%).
- Temperature in combustion chamber controlled using flue gas recirculation to 1000 °C for wood and willow and 900 °C for miscanthus, tall fescue and cocksfoot (due to ash melting at higher temperatures).
- Primary lambda varied from 0.4 to 1.2 (0.4, 0.6, 0.8, 1.0 and 1.2).

Test 2: Varying temperature: test method as described above using the following conditions:

- Total lambda of 1.6 (i.e. total excess air of approx. 8%).
- Temperature in the primary combustion chamber varied using flue gas recirculation between 900 and 1100 °C (900, 1000 and 1100 °C).
- Three primary lambda values of 0.4, 0.8 and 1.2 were tested at each temperature.
- Only one variable was changed at a time.

Test 3: Varying overall excess air ratio: test method as described using the following conditions:

- Temperature in combustion chamber controlled using flue gas recirculation to 1000 °C for wood and willow and 900 °C for miscanthus, tall fescue and cocksfoot (due to ash melting at higher temps).
- Constant primary lambda at optimum value discovered in test 1.
- Overall excess air ratio varied from 4%, 6%, 8%, 10% and 12%.

All emission data were collected and analysed using the Genstat (VSN International, Hemel Hempstead, UK) statistical analysis software and is expressed in units of mg/Nm^3 @ 13% O_2 (dry flue gas).

3. Results

The chemical properties which potentially influence NO_x and particulate emissions are shown in Table 1. Statistical significance was tested at $p < 0.001$.

The Nitrogen content of wood (0.16%) was significantly lower than all other biomass types. That of miscanthus (0.33%) was statistically greater than wood but significantly lower than willow (1.04%), cocksfoot (0.83%) and tall fescue (0.95%).

K, S and Cl are the main contributors to PM_1 emissions. Tall fescue had significantly higher levels of K (23,000 mg/kg) and S (0.22%) than all other biomass types, while its Cl content (0.13%) was second to that of miscanthus (0.14%). Cocksfoot also had relatively high levels of all 3 PM_1 forming elements with 19,400 mg/kg K, 0.12% Cl and 0.2% S. Wood with K values of 900 mg/kg, 0.03% and 0.02% respectively, and willow with K, Cl and S contents of 1400 mg/kg, 0.06% and 0.05% had significantly lower concentrations of each element than all other biomass types, with miscanthus having intermediate values of K (4810 mg/kg) and S (0.07%) but also the highest Cl content at 0.14%.

3.1. Pretest

The lowest CO emission levels (on average 18 mg/Nm^3) were achieved at a primary lambda of approximately 1.6, which equates to an overall excess air of approximately 8% (Fig. 2). A very narrow range of CO emission levels was seen for all fuels combusted with the highest being an average of 78 mg/Nm^3 from tall fescue combustion.

3.2. Primary lambda

NO_x emissions from the five Bioenergy feedstocks used in the tests were directly proportional to the quantity of fuel bound nitrogen in each feedstock. There was an easily identifiable trend (Fig. 3) for each fuel with NO_x emissions highest at the two extremes of primary air ratio, reaching their lowest values at a primary lambda of 0.8. For wood, NO_x emissions decreased significantly, by approximately 15% from a maximum of 167 at a primary lambda of 0.4 to a minimum of 142 mg/Nm^3 at 0.8 primary lambda. The highest percentage reduction in NO_x emissions was observed when miscanthus was burned with a significant decrease in NO_x emissions of 30% from lambda 1.2 (211 mg/Nm^3) to lambda 0.8 (147 mg/Nm^3). A reduction of 27% was achieved used staged air combustion for willow, while tall fescue and cocksfoot showed

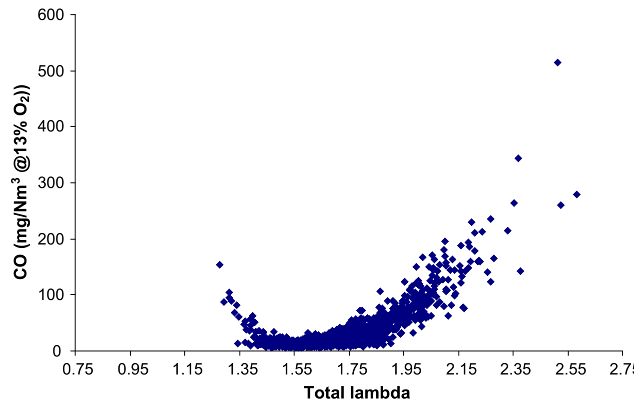

Fig. 2. Determination of optimum lambda value.

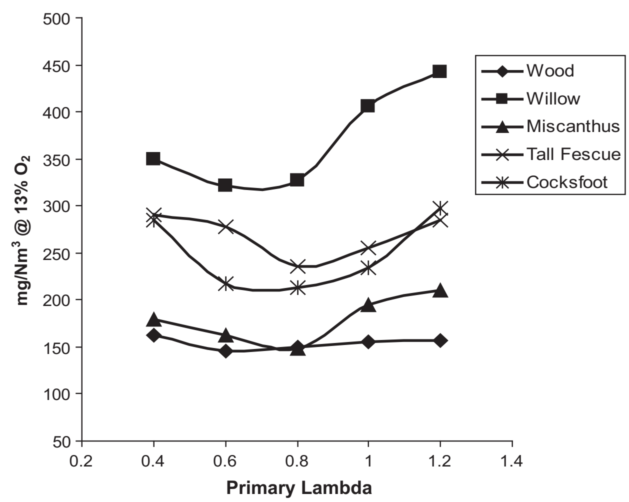

Fig. 3. The effect of primary lambda on NO_x emissions from biomass combustion.

reductions of 19% and 28% respectively. For tall fescue the NO_x emission value of 236 mg/Nm^3 at 0.8 lambda was significantly lower than for all other lambda levels, while in both willow and cocksfoot the lowest NO_x emissions were recorded at 0.6 and 0.8 lambda with no significant difference between these two primary lambda values. The reductions in NO_x emissions achieved by altering primary lambda (wood (25 mg/Nm^3) to willow (119 mg/Nm^3)) were related to the quantity of fuel bound nitrogen in the feedstock. However, the percentage reduction in NO_x emissions was unrelated to fuel bound nitrogen.

Fig. 4 shows the particulate emission trends from the air staging experiments. As can be seen in Fig. 4a there is again a trend showing highest PM_1 emissions at the 2 extremes with lowest emission values at 0.8 primary lambda. For wood, PM_1 emissions reduced significantly, by 26% from a high of 17 mg/Nm^3 at 1.2 primary lambda to a low of 12 mg/Nm^3 at 0.8 lambda. This was the highest percentage reduction of all the fuels evaluated. PM_1 emissions from willow reduced by 21% from primary lambda 1.2 (124 mg/Nm^3) to 0.8 (97 mg/Nm^3) (significant at $p < 0.001$). Particulate emissions from miscanthus were significantly reduced by 20% from 101 mg/Nm^3 at 1.2 lambda to 81 mg/Nm^3 at 0.8. For tall fescue and cocksfoot, air staging gave a significant PM_1 reduction of 20% and 16% respectively from highs at 1.2 lambda to lows at 0.8 primary lambda. Fig. 4b and c shows the effects of primary lambda on the different particulate size distributions. Particulate emissions reductions achieved through air staging were proportional to the

Table 1
Chemical composition of biomass fuels (d.b. [except Moisture content, w.b.], wt%).

	Wood	Willow	Cocksfoot	Tall fescue	Miscanthus
Calorific value (MJ/kg)	20.09	19.52	18.42	18.36	18.59
Moisture content (%)	9.2	10.4	10.2	9.8	9.6
C content (%)	50.18	48.73	48.04	48.71	48.83
H content (%)	6.08	5.85	5.67	5.94	6.31
Ash content (%)	0.31	2.22	6.12	4.96	3.56
Nitrogen content (%)	0.16	1.04	0.83	0.95	0.33
Cl content (%)	0.03	0.06	0.12	0.13	0.14
S content (%)	0.02	0.08	0.2	0.22	0.07
Si content (mg/kg)	390	480	11,600	12,300	4970
K content (mg/kg)	900	1400	19,400	23,000	4810
Ca content (mg/kg)	2700	3450	4760	4920	2300
Na content (mg/kg)	120	150	1730	2110	750
Mg content (mg/kg)	326	269	1825	1740	450

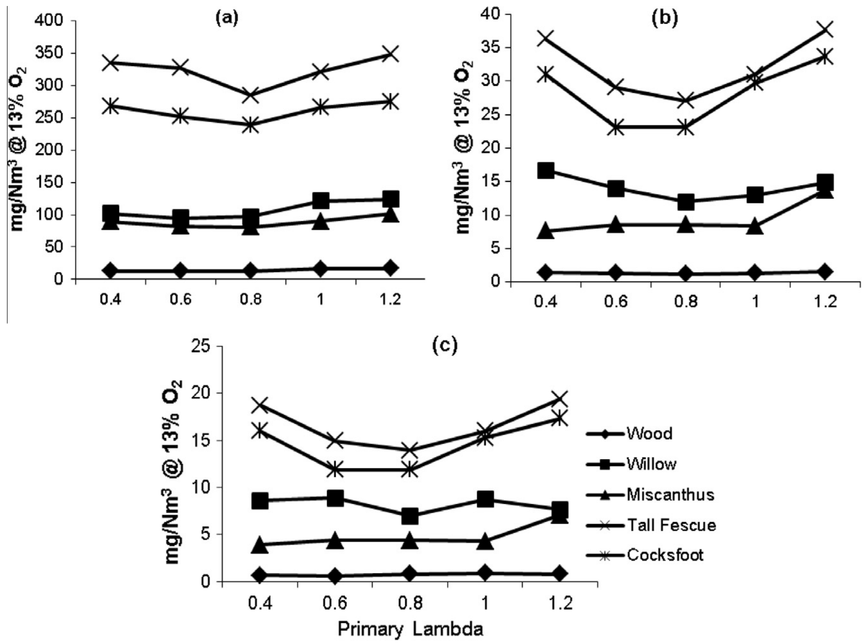

Fig. 4. Effect of primary lambda on particulate emission for (a) PM_1, (b) PM 1–10 μm and (c) PM > 10 μm.

quantities of potassium in the bioenergy feedstocks. The percentage reductions in PM_1 (wood (26%) to cocksfoot (16%)) were inversely related to the levels of total particulate emissions from each feedstock. Similar trends to PM_1 were observed for all particulate size fractions with lowest values occurring at approximately 0.8 primary lambda and reductions of the order of 20% possible with the appropriate air staging strategy. At the PM_1 size range there were significant reductions achieved by the use of air staging for all fuels. In both the PM 1–10 μm and PM > 10 μm statistically significant reductions were only found for tall fescue and cocksfoot.

3.3. Temperature

The results of Test 2 on the effects of temperature on NO_x and PM_1 emissions are shown in Table 2. This test was only completed for wood, willow and miscanthus, as at temperatures above 900 °C a large degree of ash melting was found in tall fescue and cocksfoot meaning that consistent, steady state combustion could not be achieved. As can be seen, for wood, there was no discernible pattern of NO_x or PM_1 either increasing or decreasing when temperature was changed in the primary combustion chamber. There was no significant difference between the NO_x or PM_1 emissions at the three different temperature levels. The lowest NO_x and PM_1 emissions were obtained at a primary lambda of 0.8 lambda, irrespective of temperature, as would be expected from air staging as reported above. Similar results were obtained for willow with no distinct patterns based on temperature differences emerging and no significant differences was found between average NO_x or PM_1 values at the different temperatures tested. For miscanthus at 1,100 °C the average NO_x (224 mg/Nm^3) values were significantly higher than equivalent values at 1000° (177 mg/Nm^3) and 900 °C (165 mg/Nm^3). This was also true for PM_1 with values of 126 mg/Nm^3 at 1,100 °C statistically higher than 97 mg/Nm^3 and 85 mg/Nm^3 at 1000° and 900 °C respectively. Results of a similar pattern were seen for particulate matter in the size ranges greater than 1 μm.

Table 2
Effect of primary combustion zone temperature (degree Celsius) on NO_x and PM_1 emissions (values in mg/Nm^3 @ 13% O_2).

		Wood		Willow		Miscanthus	
		NO_x	PM_1	NO_x	PM_1	NO_x	PM_1
0.4	900°	168	20	342	108	152	84
	1000°	166	16	343	103	173	99
	1100°	163	21	361	112	216	131
0.8	900°	157	19	348	98	148	79
	1000°	162	15	351	94	149	92
	1100°	151	20	355	105	201	118
1.2	900°	162	18	396	103	196	91
	1000°	179	15	452	99	211	101
	1100°	159	20	459	107	255	129

3.4. Overall excess air ratio

Test 3 was used to investigate the effects of overall excess air ratio on NO_x and particulate emissions and the results are shown in Fig. 5. There are no significant differences between the NO_x emissions at the different excess air ratios for any of the fuels tested. NO_x values from wood ranged from a high of 137 mg/Nm^3 at 8% excess O_2 to a low of 129 at 6% excess O_2. Similarly low NO_x values were seen for all other fuels with a difference between the highest and lowest emission value of just 8 mg/Nm^3 (willow), 7 mg/Nm^3 (miscanthus), 8 mg/Nm^3 (tall fescue) and 5 mg/Nm^3 (cocksfoot). Overall excess air ratio had no significant effect on PM_1 for any of the fuels tested.

4. Discussion

Emissions of NO_x during the study were proportional to fuel nitrogen content as predicted by Sommersacher et al. [1]. However, we found no relationship between percentage NO_x reduction and fuel nitrogen content although the magnitude of the reduction in NO_x emissions was related to fuel-N content. In our study, reductions in NO_x emissions of up to 30% were found to be possible using primary air staging, lower than the percentage reductions previously reported. The lower percentage reductions in NO_x emissions which we found together with the lack of a

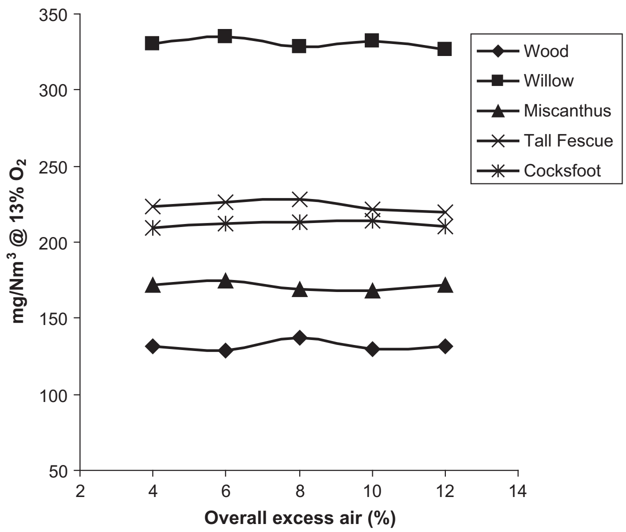

Fig. 5. Effect of overall excess air ratio on NO_x emissions.

relationship between fuel nitrogen and percentage reduction in NO_x emissions in our study may be a consequence of low residence time in the primary combustion chamber (ranging from 0.28 to 0.32 s). Biedermann [16] reported that NO_x reduction efficiency increases with increasing residence time in the primary combustion chamber and that a residence time of 0.7 s was required while Nussbaumer [10] reported that residence times greater than 0.3–0.5 s was required to optimise NO_x reduction. After a review of available literature on air staging, Biedermann [16] concluded that primary combustion chambers in residential heating boilers are often too small (short residence time) for efficient NO_x reduction.

Lowest NO_x emissions were recorded at a primary lambda of 0.8 according to the results presented in this paper. Biedermann et al. [16] reported that minimum NO_x emissions occurred at a primary lambda of 0.7–0.9 in medium sized boilers while Nussbaumer [3] reported that NO_x emissions were minimised at a primary lambda of 0.7. Houshfar et al. [11,17] reported optimum primary excess ratios of 0.8 to 0.95. Thus, our own results and other studies suggest that NO_x emissions are minimised at a primary lambda slightly less than 1. Critically, the optimum primary lambda was the same for all of the fuels tested in this study irrespective of fuel nitrogen content within the range of fuels used in this study. Similarly, Houshfar et al. [17] investigated the effect of primary air on the NO_x emissions from the combustion of a range of fuels and mixtures with a wide range of nitrogen contents and found that the optimum primary air ratio for all fuels and mixtures was 0.9–0.95, the only exception being one mixture where melted ash had an effect on combustion. Hence, it would appear that the optimum primary air ratio is independent of the fuel used for any given technology whereas the actual primary air ratio at which NO_x emissions are minimised is a characteristic of the technology/boiler design.

It was shown that PM_1 emissions could be reduced by up to 26% by adjusting primary air ratio. This reduction is caused by a decrease 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 and thus ends up in the grate ash fraction rather than as a particulate emission [3]. Nussbaumer [3] showed that a TSP reduction by a factor of 5 is possible by optimising primary air ratio. Lamberg et al. [15] found that PM_1 emissions could be reduced from 12.2 mg/MJ to 3.0 mg/MJ by primary air reduction and attributed the reduced particulate emissions to a decrease in the temperature of the primary combustion zone and to a consequent reduced volatilization of alkali metals in the fuel bed. For all fuels, particulate emissions were minimised at a primary air ratio of 0.8 suggesting that the optimum primary air ratio for particulate emission reduction is determined by the technology rather than the fuel. In our study, emissions of both NO_x particulates were minimised at the same primary air ratio in spite of the fact that different mechanisms are involved in each case. This finding suggests that the reducing atmosphere in the primary combustion chamber which minimises NO_x emissions is also conducive to the reduction of particulate emissions through an effect on temperature as suggested by Lamberg at al. [15]. Particulate reduction efficiency decreased from 26% for the fuel with the lowest particulate emissions to 16% for the fuel with the highest particulate emissions. As discussed above for NO_x emission reductions, this effect may have been caused by inadequate residence time in the primary combustion chamber.

Skreiberg et al. [18] working on single pellets with no air staging reported that emissions of nitric oxide from wood particles increased with increasing temperature up to 1073 K before decreasing. In contrast, Houshfar et al. [11] found that changing temperature from 850 to 1000 °C had no effect on NO_x emissions when demolition wood with a nitrogen content of 1.06% was combusted in a grate combustion multifuel reactor. We found that temperature had no effect on particulate and NO_x emissions from wood combustion. However, emissions of NO_x from miscanthus increased with increasing temperature when miscanthus was burned while a weaker effect was observed for willow. Thus, this effect was unrelated to fuel nitrogen content as the nitrogen content of the miscanthus used in this study was lower than that of willow. In the case of miscanthus, increased emissions at higher temperatures may be related to poor combustion conditions once ash begins to melt as miscanthus has a relatively low ash melting temperature. In any case, the results suggest that emissions of both particulates and NO_x can be minimised by using lower temperatures circa 900 °C. This result may well be technology specific as Nussbaumer [3] concluded that much higher temperatures were necessary for optimum NO_x reduction, Biedermann et al. [16] reported that a minimum temperature of 800 °C in the primary combustion chamber was necessary for reduced NO_x emissions.

Biedermann et al. [16] reported from Austrian work that NO_x emissions decreased with total air ratios. Houshfar et al. [11] reported that NO_x emissions increase total excess air up to a value of approximately 1.5 before decreasing. In contrast, Lamberg et al. [15] found that particulate emissions increased when secondary air supply was decreased and concluded that sufficient input of secondary air together with good mixing is important to reduce particulate emissions. However, our results show that for this technology no further reduction in emissions is possible by adjustment of secondary air once the optimum primary air ratio is used. Again, this result may well be technology specific. There was no physical separation between the primary and secondary combustion chambers in the boiler used for the tests described in this study.

5. Conclusions

Pollutant emissions from the combustion of a range of Bioenergy feedstocks can be reduced using air staging strategies. Emissions of particulates and oxides of nitrogen can be minimised by optimising primary air ratio and by keeping the temperature in the primary combustion chamber at approximately 900 °C. Both particulate and NO_x emissions were minimised at a primary lambda of 0.8, optimum primary lambda value was independent of biomass feedstock. Reductions in NO_x and particulate emissions of up to 30% were shown to be possible in this study; further reductions may be possible in biomass combustion systems with long residence times in the primary combustion chamber.

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References

[1] Sommersacher P, Brunner T, Obernberger I. Fuel indexes: a novel method for the evaluation of relevant combustion properties of new biomass fuels. Energy Fuels 2012;26(1):380–90.
[2] Nussbaumer T. Combustion and co-combustion of biomass: fundamentals, technologies and primary measures for emission reduction. Energy Fuels 2003;17:1510–21.
[3] Dockery DW, Pope CA, Xu X, Spengler JD, Ware JH, Fay ME, et al. An association between air pollution and mortality in six US cities. New Engl J Med 1993;329:1753–9.
[4] EEA. Air quality in Europe – 2012 report. European environment Agency report no 4/2012; 2012. ISSN 1725-9177, <http://www.eea.europa.eu/publications/air-quality-in-europe-2012/view - accessed 12/1/2013>.
[5] Van Loo S, Koppejan J. The handbook of biomass combustion and co-firing. ISBN 978-1-84407-249-1. EARTHSCAN, London and Sterling, VA; 2008.
[6] Bäfver LS, Rönnbäck M, Leckner B, Claesson F, Tullin C. Particle emission from combustion of oat grain and its potential reduction by addition of limestone or kaolin. Fuel Process Technol 2009;90:353–9.
[7] Carroll J, Finnan J. The use of additives and fuel blending to reduce emissions from the combustion of agricultural fuels in small scale boilers. Biosyst Eng 2015;129:127–33.
[8] Fagerström J, Nyström I, Boström D, Öhman M, Boman C. Reduction of fine particle- and deposit forming alkali by co-combustion of peat with wheat straw and forest residues. Proc. Impacts of Fuel Quality on Power Production and Environment. 29 August–03 September 2010, Saariselkä, Finland; 2010.
[9] Salzman R, Nussbaumer T. Fuel staging for NO_x reduction in biomass combustion: experiments and modelling. Energy Fuels 2001;15:575–82.
[10] Nussbaumer T. Primary and secondary measures for the reduction of nitric oxide emissions from biomass combustion. In: Developments in thermochemical biomass conversion. Blackie Academic and Professional; 1997.
[11] Houshfar E, Skreiberg O, Lovas T, Todorovic D, Sorum L. Effect of excess air ratio and temperature on NO_x emission from grate combustion of biomass in the staged air combustion scenario. Energy Fuels 2011;25:4643–54.
[12] Houshfar E, Khalil RA, Lovas T, Skreiberg O. Enhanced NO_x reduction by combined staged air and flue gas recirculation in biomass grate combustion. Energy Fuels 2012;26:3003–11.
[13] Houshfar E, Skreiberg O, Todorovic D, Skreiberg A, Lovas T, Jovoviv A, et al. NO_x emission reduction by staged combustion in grate combustion of biomass fuels and fuel mixtures. Fuel 2012;98:29–40.
[14] Eskilsson D, Ronnback M, Samuelsson J, Tullin C. Optimisation of efficiency and emissions in pellet burners. Biomass Bioenergy 2004;27:541–6.
[15] Lamberg H, Sippula O, Tissari J, Jokiniemi J. Effect of operating conditions on emissions from a small scale pellet boiler. Energy Fuels 2011;25:4952–60.
[16] Biedermann F, Brunner T, Obernberger I, Sippula O, Boman C, Öhman M, et al. Summary and evaluation of existing strategies on air staging strategies. Report produced as part of the ERANET Futurebiotec project; 2010, <http://futurebiotec.bioenergy2020.eu/files/FutureBioTec-Summary%20and%20Evaluation%20of%20Air%20Staging%20Strategies.pdf accessed 5/2/2013>.
[17] Houshfar E, Lovas T, Skreiberg O. Experimental investigation on NO_x reduction by primary measures in biomass combustion: straw, peat, sewage sludge, forest residues and wood pellets. Energies 2012;5:270–90.
[18] Skreiberg O, Glarborg P, Jensen A, Dam-Johansen K. Kinetic NO_x modelling and experimental results from single wood particle combustion. Fuel 1997;76(7):671–82.