Energy 141 (2017) 2069–2080

Contents lists available at ScienceDirect

Energy

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

Experimental investigation of woody and non-woody biomass combustion in a bubbling fluidised bed combustor focusing on gaseous emissions and temperature profiles

Farooq Sher, Miguel A. Pans, Daniel T. Afilaka, Chenggong Sun, Hao Liu*

Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form
19 November 2017
Accepted 20 November 2017
Available online 21 November 2017

Keywords:
Bubbling fluidised bed combustor
Biomass fuels
Air staging
NOx emission
CO emission

ABSTRACT

Air staging is a well-known effective method to control NOx emissions from solid fuel combustion boilers. However, further research is still needed to clarify the effect of air staging at different injection locations on the gaseous emissions of Fluidised Bed Combustion (FBC) boilers that fire 100% biomass fuels, particularly non-woody biomass fuels. The main objective of this work is to investigate the effect of the staging air injection location on the gaseous emissions (NOx and CO) and temperature profiles of a 20 kW_{th} bubbling fluidised bed combustor firing three non-woody (straw, miscanthus and peanuts) and two woody biomass fuels. The experimental results showed that injecting the secondary air at the higher location could lead to a greater NOx reduction due to the fact that the biomass combustion reaction mainly took place in the splash zone and/or beginning of the freeboard. Up to 30% of NOx reduction, compared with no air staging, was achieved for the non-woody fuels when the staging air was injected at the higher-location. Air staging also significantly reduced the CO emissions as a result of the higher temperatures in the freeboard and longer residence time in the primary combustion zone.

1. Introduction

The UK government recently announced its intention to close all of the UK's coal-fired power plants within 10 years [1]. According to this, more electricity will be expected to be generated from natural gas in tandem with nuclear and renewables. As a renewable and carbon-neutral source of energy, biomass can play an important role in CO_2 emissions mitigation and be an alternative to the carbon-intensive and 'dirty' fossil fuel, coal, for power generation. In recent years, woody biomass has been widely used as a fuel in the energy sector [2–4]. For example, 70% of the electricity generated by the UK Drax Power Station which is responsible for generating 7% of the UK electricity, is produced by use of compressed wood pellets [4]. However, increasing demand for woody biomass from the energy sector, sawmills as well as pulp and paper industries, results in an increase in the price of wood [5]. Limited and more expensive wood fuel supplies are forcing the energy sector to consider the utilisation of low-quality woody materials and non-woody biomass, such as agricultural crops and agricultural and forest residues.

The specific properties of biomass materials (e.g. low energy density, low ash melting point, varying moisture content) can pose many operational challenges to biomass combustion boilers. Fluidised bed combustion (FBC) boilers have been increasingly used to burn difficult to use fuels such as biomass waste materials over the past decades. In a FBC boiler, the fuels are burned in a turbulent bed of an inert solid bed material, thus ensuring high heat transfer rates, excellent gas-solid mixing and good combustion efficiency, at typical combustion temperatures of 800–900 °C. Although the NOx (NO and NO_2) emissions from FBC boilers are considerably lower than those of pulverised fuel (PF) combustion boilers, largely due to their combustion temperature (800–900 °C) being much lower than the typical combustion temperature of PF boilers (1300–1700 °C), emissions (NOx, CO and particulates etc.) are still a major issue for biomass combustion systems. Biomass combustion systems emit relatively high levels of NOx and particulates in comparison to the combustion systems of light fuel oil or natural gas. The life cycle assessment (LCA) indicates that almost 40% of the environmental impact of a modern automatic wood furnace is associated with NOx emissions [6].

Among all of the NOx control/reduction technologies (air

* Corresponding author.
E-mail address: liu.hao@nottingham.ac.uk (H. Liu).

https://doi.org/10.1016/j.energy.2017.11.118
0360-5442/

staging, fuel staging, selective non-catalytic reduction (SNCR), selective catalytic reduction (SCR) etc.), air staging is the most widely applied because of its low cost and easy for implementation [7–9]. When air staging is applied to a fluidised bed boiler, the combustion air is separated into the primary air stream, which is also the fluidising air supply to the bed, and the secondary air stream that is injected higher up in the bed or freeboard. As all of the biomass fuel is fed to the primary combustion region (the bed), the bed can be maintained at substoichiometric conditions, hence limiting the oxidation of fuel-nitrogen and reducing the already formed NO by homogeneous reactions with the radical-pool or by the heterogeneous reactions with the char [10,11]. In addition, the substoichiometric conditions decrease the bed combustion temperature and increase the CO concentration in the bed, both of which contribute to lower NOx emissions [12–17]. Combustion is completed following the introduction of the secondary air to burn out the carbon monoxide and other unreacted combustible gases. Similar to fixed bed combustion and PF combustion, fluidised bed combustion also needs to be operated with a suitable level of overall excess air to ensure complete combustion can be achieved under both air staging and non-air staging conditions.

The success of air staged combustion technique to control NOx emissions may strongly depend on, among other variables, the secondary air ratio and the location of the secondary air injection. A number of groups of researchers have studied the effect of air staging on NOx emissions focusing on the effect of the secondary air ratio while firing biomass fuels in fluidised beds [18–25]. However, the research found in the literature investigating the effect of the secondary air injection location on NOx emissions when applying air staging in biomass fluidised beds is quite scarce. Saikaew et al. [26] investigated NOx emissions for the co-combustion of subbituminous coal with four kinds of biomass (palm shell, coconut shell, sawdust and rice husk) in a circulating fluidised bed combustor with the secondary air injected into the riser at different heights. They found that NOx emissions decreased considerably when the location of the secondary air moved upward from 1 m to 2.4 m. Varol et al. [27] also studied the effect of the position of the secondary air injection on the flue gas emissions in the co-combustion of woodchips and lignite in a 30 kW_{th} CFB combustor. They concluded that the higher the secondary air injection position, the lower the NO emission. However, in both cases, the research was focused on the co-combustion of biomass and coal, rather than the combustion of 100% biomass fuels.

The properties of biomass and coal differ in many important ways, which can result in completely different combustion behaviours [28]. One of these remarkable differences is related to the volatile matter content and volatile combustion: in comparison with coal, biomass can lose up to 90% of its mass in the first stage of its combustion. As a consequence, the most part of biomass combustion in a FBC combustor takes place in the upper part of the combustor, resulting in the freeboard region of the combustor to have major roles for NOx emissions and their controls through combustion modification methods, for example, air staging. Hence, a comprehensive study of the effect of the secondary air injection location along the freeboard on NOx emissions in fluidised bed combustors when burning 100% biomass fuels, and particularly non-woody biomass fuels, is needed for better NOx emissions control and better understanding of the combustion behaviour of these kind of fuels in FBC boilers/combustors. In addition, literature survey confirms that most of the previous studies on the fluidised bed combustion of non-woody biomass fuels are almost exclusively focused on the agglomeration phenomena, rather than the gaseous emissions or the effect of air staging on the gaseous emissions. In one of the latest studies published to date, Ninduangdee and Kuprianov [29] performed a study on the combustion of oil palm empty fruit bunch in a fluidised bed, investigating the effect of excess air and bed material on gaseous emissions and fluidisation behaviour. However, the effect of air staging on gaseous emissions was not considered in this work. Duan et al. [18] conducted a series of experiments on the combustion of peanut shells in a vortexing fluidised bed combustor under air staging conditions. Nevertheless, the influence of the secondary air injection location on the gaseous emissions was not investigated in their work.

The main objective of the present work is to systematically study the effect of the secondary air injection location on the gaseous emissions (NOx and CO) and temperature profiles with the combustion of three different non-woody biomass fuels (straw pellets, peanut shell pellets and miscanthus pellets) and two woody biomass fuels (domestic wood pellets and industrial wood pellets) in a 20 kW_{th} bubbling fluidised bed (BFB) combustor, working at different excess air levels.

2. Experimental setup

2.1. Materials and fuels characteristics

Two woody biomass fuels, domestic wood and industrial wood, and three non-woody biomass fuels, miscanthus, straw and peanut shell, were selected for the combustion tests of this study. All fuels were used in pellet form with a diameter of ca. 6–8 mm and length of ca. 14–23 mm. The proximate and ultimate analyses and physical properties of the fuels are shown in Tables 1 and 2, respectively. Garside 14/25 sand with a Sauter mean diameter (d_{32}) of 0.78 mm and a density of 2655 kg/m^3 was used as the inert bed material [30]. The main chemical compounds of the sand are SiO_2 (96.67 wt.%), Fe_2O_3 (2.40 wt.%) and Al_2O_3 (0.33 wt.%).

2.2. Experimental system of 20kW$_{th}$ BFB biomass combustor

The experimental system, shown in Fig. 1, mainly includes a bubbling fluidised bed (BFB) combustor (20 kW_{th}) and the auxiliary systems for air supply, biomass feeding, and gas analysis. The combustor consists of a stainless steel reactor of 102 mm i. d. and 800 mm height, a freeboard of 154 mm i. d. and 1100 mm height, and a plenum of 102 mm i. d. and 300 mm height. A water cooled heat extraction probe located inside the bed allows the bed temperature to be controlled by means of the extraction of heat from the combustor and to prevent the bed from reaching very high temperature values, thus avoiding agglomeration and defluidisation of the bed particles. The cooling water flow rate of the probe can be adjusted to control the heat extraction and hence the combustion temperature inside the reactor.

The combustion and fluidisation air is supplied from a blower with the flow rate controlled by means of a ball valve and monitored by a rota meter. The air is fed into the combustor through a porous stainless gas distribution plate with 100 μm pore size and 12 mm thickness. An electric air pre-heater before the plenum and two electric half-cylindrical ceramic radiant heaters surrounding the main bed area are used to preheat the combustion/fluidisation air during the start-up of the combustor. The biomass pellets are fed to the combustor at the location just above the distributor plate by means of a screw feeder. To ensure the fuel feed rate controllable and repeatable, the feeder motor frequency is controlled by an inverter. A small proportion of air is also fed through the biomass feeder hopper to prevent backfire and to stop the sand particles coming into the fuel feeding pipe.

Under the air staging conditions, the secondary air supplied by an air compressor and controlled by a mass flow controller can be introduced to the combustor at two different locations: either at 70 cm or 110 cm above the distribution plate. The flue gas stream

Table 1
Proximate and ultimate analyses of the studied biomass fuels.

Biomass Fuels	Ultimate analysis (wt%)[a]					Proximate analysis (wt%)[c]				LHV[d] MJ/kg
	C	H	N	O[b]	S	M	VM	FC[b]	Ash	
Domestic wood	47.18	6.84	0.17	45.64	0.17	3.94	85.11	14.19	0.70	17.49
Industrial wood	47.57	6.95	0.26	45.01	0.21	5.34	85.00	13.72	1.28	17.48
Miscanthus	45.87	6.74	0.38	46.82	0.19	3.34	82.85	15.35	1.80	16.95
Straw	43.80	6.78	0.55	48.29	0.58	5.22	76.31	17.46	6.23	15.72
Peanut shell	46.97	6.79	1.34	44.39	0.51	5.96	74.06	22.39	3.55	17.04

M – Moisture; VM - Volatile matter; FC - Fixed carbon.
[a] On dry-ash-free basis.
[b] Calculated by the difference.
[c] On dry basis except for moisture which is on an as received basis.
[d] Low heating value (dry basis).

Table 2
Physical properties of the studied biomass pellet fuels.

	Diameter (mm)	Length (mm)	Bulk density (kg/m^3)
Domestic wood	6.00	23.10	677
Industrial wood	6.40	17.45	574
Miscanthus	6.30	18.70	603
Straw	6.15	15.60	628
Peanut shell	8.25	14.20	532

leaving the combustor passes through a high efficiency cyclone to recover the elutriated solids and ash and then is exhausted through the ventilation system. The gas composition at the exit of the combustor is continuously analysed by on-line gas analysers after going through the sampling line of a sampling pump, water condensation traps and particle filters. O_2, CO_2 and CO concentrations are measured by an Easy line continuous gas analyser (ABB, EL3020) which can also measure nitric oxide (NO), while the NOx concentration is measured by a chemiluminescent NOx analyser (Horiba VA-3000). The analysers were frequently calibrated with the certified calibration gases supplied by BOC of the Linde Group in order to minimise instrumental errors. The combustor is equipped with pressure tapings and sheathed K-type thermocouples at different heights. A data taker system connected with a computer is used to continuously record all of the measured process data (pressure differentials, temperatures, gas composition, etc.). Both the pressure differential across the dense bed and the temperatures along the reactor are closely monitored during each test so that any signs of agglomeration, defluidisation or extremely high temperature can be spotted at the earliest opportunity. Previous research [31] has reported that sudden changes in the pressure differential across the bed and temperatures during operation may mean defluidisation. However, it is worth mentioning that the focus of the present work was on the gaseous emissions and temperature profiles but not on the agglomeration phenomenon and mechanisms. Therefore, in order to avoid agglomeration, almost all of the tests reported in the present study were carried out at relatively low bed temperatures (700–820 °C), except when firing industrial wood at low excess air levels, where a bed temperature of 850 °C was reached due to the higher calorific value of this fuel (Table 1) and the use of a low cooling water flow rate at 1 L/min (Table 3). As a consequence of low combustion temperatures being maintained with the tests, no signs of agglomeration and/or defluidisation were detected during the whole operation period of this study, which included the testing of all 5 biomass fuels under all different operational conditions with the total accumulated operational time of more than 100 h. In addition, no agglomerates were found in bed materials after careful post-combustion inspection of the bed materials with each biomass fuel.

2.3. Experimental procedure and conditions

The operating conditions for all tests are summarised in Table 3. Before each set of tests, the bed was filled with 3.2 kg of Garside sand, which means a bed height of about 25 cm. As an example, Fig. 2 shows the temperature profiles, measured at different heights of the bed and freeboard, the differential pressure drop in the bed and the gas composition at the outlet of the combustor obtained with a typical experiment. Initially, the bed was heated up with the main ceramic heaters installed along the walls of the main bed area. Hot air was then introduced through the pre-heater to stir and fluidise the bed particles. Once the bed temperature (thermocouple point T-2 at Fig. 1) reached the required fuel ignition temperature (>ca. 500 °C), the biomass feeding was started and the bed temperature rose abruptly due to the biomass combustion. Once proper biomass combustion was established, the main electric heaters and the preheater were switched off, and the cooling probe was introduced into the combustor to control the bed temperature. As a result of the heat extraction with the cooling probe from the combustor, the measured gas temperatures inside the combustor were seen to be slightly decreasing until reaching steady values. All of the results reported in this paper were those obtained with the continuously feeding BFB combustor operating under steady state conditions. The gas composition at the outlet of the combustor and the temperature profiles along the combustor were uniform during each formal test period under every condition studied and this was the case for all of the five biomass fuels studied, with and without air staging.

To analyse the effect of excess air on the flue gas emissions, the experiments were carried out by varying the fuel feeding rate and maintaining a constant total air flow rate at 350 L/min. When the fuel feeding rate was varied, the temperatures along the reactor and freeboard were varied simultaneously as the water flow rate and position of the heat extraction probe remained unchanged. To investigate the effect of the air staging, part of the total air flow rate (50 L/min) was diverted to one of the two air staging injection pipes, while the total air flow rate was fixed at the constant value of 350 L/min. In order to study how the air staging injection location effects to the gas compositions, the secondary air was injected from two different heights: 70 cm (namely AS1) and 110 cm (namely AS2) from the distributor plate. For comparison purposes, experiments without air staging (namely WAS) were also carried out with all the fuels. At least three runs were performed with each biomass for each condition studied (WAS, AS1 and AS2), in order to verify the results achieved.

3. Results and discussion

3.1. Effect of excess air on NOx and CO emissions

Fig. 2 shows the effect of the excess air on the temperature

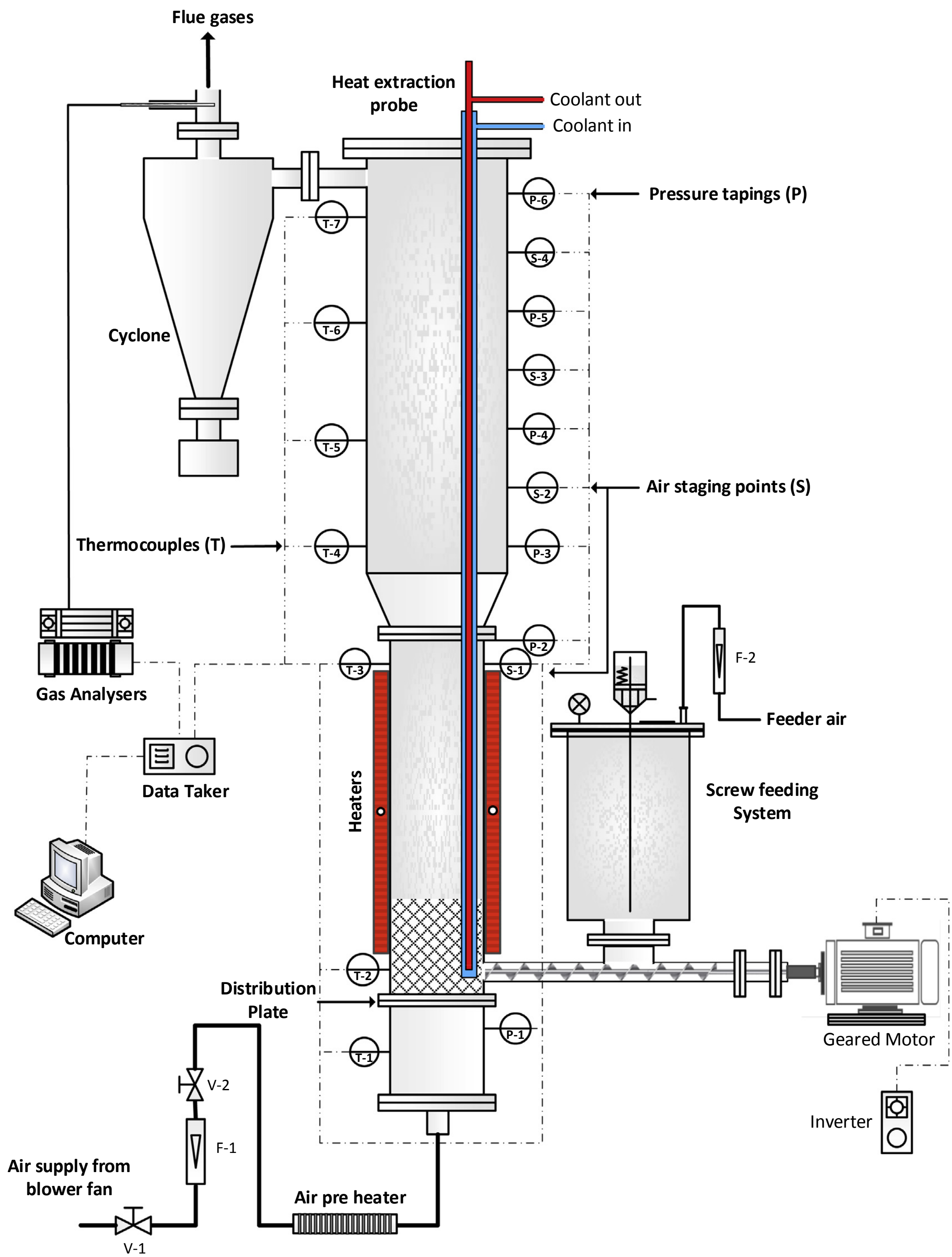

Fig. 1. Schematic of the 20 kW_{th} BFB combustor experimental system.

profiles, the pressure drop across the bed and the gas composition at the outlet of the reactor burning miscanthus pellets under WAS conditions. As it can be seen from the figure, temperatures along the combustor and the CO_2 concentration at the outlet of the reactor decrease with the excess air level. As explained in the experimental procedure and conditions Section (2.3), during the experiments the total air flow rate was maintained constant, and the stoichiometry or the excess air level was modified by changing the biomass feed rate, and therefore a higher excess air level was achieved with a lower biomass feed rate. A lower biomass feed rate had led to a less amount of heat released and less amount of CO_2 generated in the combustor. An increase in the excess air also led to a decrease in the CO concentration at the outlet due to the better combustion efficiency achieved. An increase in the excess of air resulted in an increase in the NOx concentration at the outlet as a result of the higher oxygen concentration in the combustor: a higher oxygen concentration favours the formation of NOx in the dense bed due to the enhanced combustion of the volatile matter

Table 3
BFB combustor operating conditions.

Parameters	Values
Biomass feed rate (kg/h)	3–5
Average bed material diameter (mm)	0.78
Bed height (mm)	250
Total air flow rate (L/min)	350
Minimal fluidisation velocity (m/s)[a]	0.28
Superficial gas velocity (m/s)[a]	2.64
Secondary air (air staging) flow rate (L/min)	50
Excess air (%)	10–55
Bed temperature range (°C)	700–850
Preheater temperature set-up (°C)	450
Cooling water flow rate (L/min)	1–1.4

[a] At 800 °C.

and char and the conversion of fuel-N to NOx in an oxygen rich atmosphere. In addition, a higher oxygen concentration enhances the combustion efficiency which results in lower char and CO concentrations throughout the combustor, reducing the effect of NO reductions by CO and char [11,32]. These results agree with the findings of other researchers [33]. The effect of excess air on NOx and CO emissions was found to be similar in all the experiments performed with the five biomasses tested, with and without air staging.

3.2. Effect of biomass composition on NOx emissions

During the combustion process of each biomass fuel, NOx can be formed through three main reaction mechanisms, i.e. the prompt-NOx, the thermal-NOx and the fuel-NOx formation mechanisms [9]. Both prompt- and thermal-NOx are formed from nitrogen in the air but thermal-NOx are formed at elevated temperatures and prompt-NOx are formed with the presence of hydrocarbons. Furthermore, fuel-NOx formed from the fuel-N contained in the fuel are likely to be the main part of the overall NOx formed in the combustion process of a solid fuel such as coal and biomass. Fig. 3a shows the effect of the excess air on the NOx emissions for the five fuels used in this study, without using air staging, whereas Fig. 3b shows the fuel-N content of the five fuels listed in Table 1. The results shown in Fig. 3 clearly indicate that the higher the fuel-N content, the higher the NOx emissions at the outlet of the reactor, and this agrees with the expectation that the majority of the NOx are originated from the fuel-N. Prompt-NOx and thermal-NOx weren't expected to be of importance due to the relatively low combustion temperatures reached at the reactor (as seen in Table 3 and Fig. 2). In fact, most fluidised bed systems usually work below 900 °C and hence the formation of thermal-NOx and prompt-NOx are always expected to be of insignificance for coal-fired or biomass-fired fluidised bed combustors/boilers [6,34]. Duan et al. [35] reported similar findings with biomass combustion in a circulating fluidised bed combustor. As peanut shell pellets have the highest fuel-N content, their combustion in the fluidised bed combustor without air staging have led to considerable NOx emissions (up to 450 ppm) which are higher than the NOx emitted by the combustion of any other fuels under the same test conditions. In general, agricultural lignocellulosic biomasses have higher fuel-N contents than woody biomasses [36] and hence their combustion will lead to higher NOx emissions if there is no proper NOx abatement strategy being incorporated in the combustion system. The two woody biomasses (the industrial wood pellets and the domestic wood pellets) are the two fuels with the lowest fuel-N contents and therefore their combustion in the fluidised combustor emits the least amounts of NOx, less than 20% of that emitted by the combustion of peanut pellets at high excess air levels.

3.3. Effect of air staging at two different injection points on temperature profiles

Fig. 4 shows the temperature profiles along the reactor/freeboard for all of the tested biomass fuels at two overall excess air levels (10% and 50%) and operating under WAS, AS1 and AS2 conditions. The heights of the two air staging injection points studied, AS1 and AS2 are indicated in each graph in Fig. 4. As expected, working under WAS conditions, the maximum temperature is reached at the splash zone and/or beginning of the freeboard, above the dense bed. The temperature peak observed at these regions is attributed to the characteristic high volatile matter content of biomass fuels and to its release and combustion mostly in the splash zone and freeboard, instead of inside the dense bed as observed in the case of low volatile matter content coal combustion [37]. Other authors reported similar results [38]. This behaviour occurs as a result of; i) segregation of fuel particles during devolatilisation at the top of the bed [39,40] (irrespective of the feeding options including the feeding into the bed option as used in this study), and ii) limited in-bed volatile matter combustion [41]. The segregation of biomass fuel particles at the bed surface during devolatilisation has been well documented [39,40], and is believed to be related with the lift effect that the volatile bubbles can exert on fuel particles. After the temperature peak, a remarkable temperature decrease in the freeboard above 1.00 m is observed, due to the fact that heat extracted by the water cooling probe from the upper part of the freeboard is much higher than the heat released from the combustion of any unburned fuels within the freeboard.

As it can also be observed from Fig. 4, straw combustion gives a much different temperature profile from any other fuels studied, i.e. much higher temperatures in the splash region in comparison to the bed region. As the volatile matter content is similar for all the fuels (Table 1), the differences in the temperature profiles between the straw and the rest of the fuels could be partly due to the difference in the content of fines in the fuels. Straw pellets have a higher fraction of fines than any other pellet fuels used in this study. A higher level of fines implies that a larger fraction of the straw fuel is expected to be burned in the splash zone/freeboard region instead of the dense bed of the reactor and hence leads to a higher temperature difference between the splash region and the bed in comparison to the other fuels. Because of this, the D-shape of the temperature profile along the reactor is more pronounced in the case of straw.

Also shown in Fig. 4, using air staging (AS1 or AS2) when operating with the overall excess air level at 10%, there was a significant increase in the temperatures in the splash region and freeboard in almost all the cases (see the shaded areas in Fig. 4) compared with those under WAS conditions. This increase in temperatures suggests there is a significant amount of unburned gases and volatile matter in the splash zone and freeboard, as a result of sub-stoichiometric combustion conditions in the dense bed region, and further combustion of the unburned fuels in the splash zone and freeboard after the injection of the secondary air. On the other hand, when air staging is operated under the condition of 50% overall excess air, similar or lower temperatures than those measured under WAS conditions were observed along the reactor/freeboard for all fuels: a higher overall excess air level implies a higher combustion efficiency can be achieved at the lower part of the reactor (in the dense bed region, especially) and therefore much less unburned gases and volatile matter reach the splash zone and freeboard. The results in Fig. 4 also show that in many cases there is a temporary decrease in the temperature immediately after the injection of the secondary air. This happens because the secondary air is not preheated and hence at a temperature much lower than the primary combustion gas

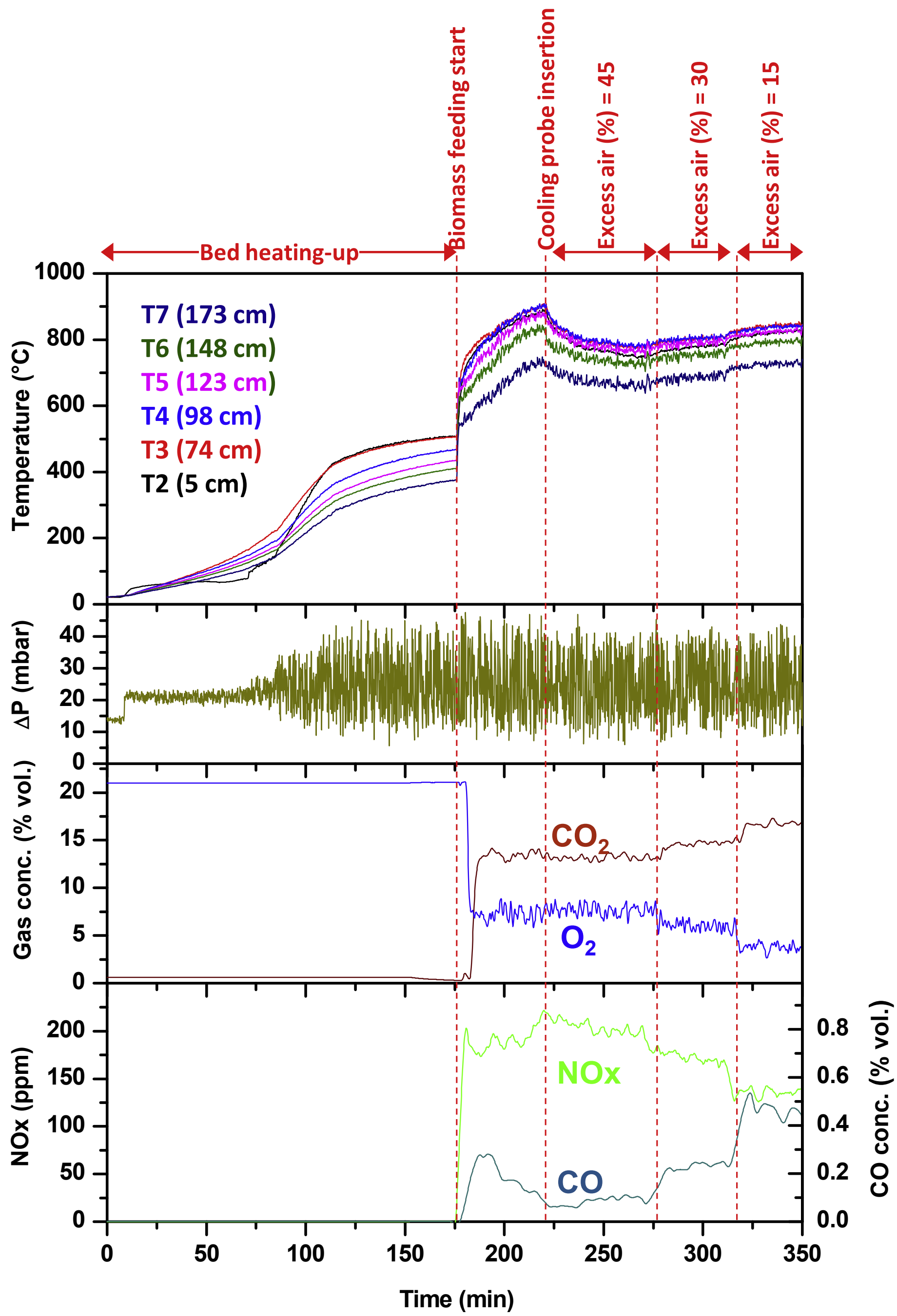

Fig. 2. Temperature profiles at the different heights of the reactor and freeboard, the pressure drop across the dense bed, and the gas composition (CO_2, O_2, NOx and CO) at the outlet of the reactor during a typical experiment. fuel used - miscanthus, combustion conditions - WAS (without air staging).

temperature before entering the combustor. The temporary decrease is more pronounced when the secondary air is injected at AS1 as there is a thermocouple near to this injection point.

3.4. Effect of air staging at two different injection points on NOx emissions

Fig. 5 shows the effect of excess air on NOx emissions for all tested biomass fuels with the fluidised bed combustor operating without air staging (WAS) and with air staging at two different injection points (AS1–70 cm and AS2 - 110 cm from the distribution plate). Injecting the secondary air at the lower point (AS1) led to a decrease in the NOx emissions when the peanut shell pellets or the miscanthus pellets were used as the fuel; whereas for other fuels, air staging at AS1 did not lead to a decrease but a small increase in the NOx emissions. On the contrary, a significant decrease in the NOx emissions was achieved with almost all of the fuels (except when using domestic wood) when the secondary air was injected at the higher point (AS2). As pointed out in the Introduction Section, the reduction of NOx emissions achieved with air staging is mainly due to the decrease of the oxygen-to-fuel ratio in the primary combustion region, which limits the oxidation of fuel-nitrogen to NOx [42]. In addition, the reduced availability of oxygen leads to higher concentrations of NOx reducing species such as

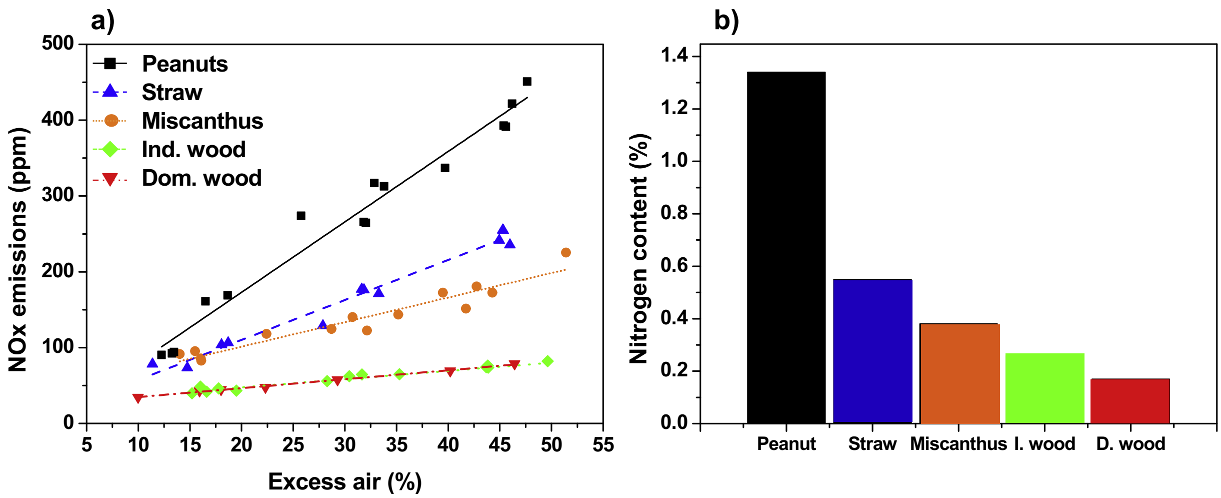

Fig. 3. a) Effect of excess air on NOx emissions for all the biomass fuels tested without air staging. b) The nitrogen content of the different biomass fuels. NOx emissions are expressed as parts per million (ppm) on a dry basis, corrected 6% O_2 in the flue gas.

CO which can also contribute to the catalytic reduction of NOx on the char surfaces [17]. After the injection of the secondary air, most of CO and other unburned gases are fully combusted before the exhaust. The best results achieved under AS2 conditions, in terms of the extent of NOx reduction accomplished, can be explained by means of the characteristic combustion behaviour of biomass fuels. As it has been shown in Section 3.3, the temperature profiles obtained with all of the tested fuels suggest that the main combustion reaction (and therefore the formation of NOx) takes place in the splash zone and/or beginning of the freeboard due to the characteristically high volatile matter content of biomass, which implies a larger contribution of volatile-N (i.e. fuel-nitrogen released with the volatiles) on the formation of NOx, in comparison to the contribution of the char-N (i.e. the fuel-nitrogen remaining in the char) [43]. Thus, the secondary air with air staging should be introduced higher up the combustor in order to make air staging more effective in reducing NOx emissions. The lower secondary air injection point (AS1) is located precisely in the splash zone/beginning of freeboard, where the main combustion reaction takes place and where the maximum temperatures are reached. Therefore, the injection of the secondary air at this point provides the oxygen needed to promote the oxidation of fuel-N in a high temperature zone, and hence favours the formation of NOx as observed with the cases of straw, industrial and domestic wood. These results agree with those obtained by Saikaew et al. [26] and Varol et al. [27] who also found the lowest NOx emissions under air staging conditions with the secondary air injection at the highest position when co-firing coal and biomass in fluidised bed combustors. In the work of Saikaew et al. [26], the decrease in NOx emissions was explained by the fact that when the secondary air injection was located in the upper zone (2.4 m), the influence of oxygen on the fuel-N oxidation was small since the temperature in the upper region was much lower than the lower region next to the distributor. In the present work, on the contrary, both air staging injection points are located in the high-temperature zone, due to the high volatile matter content of biomass fuels, and therefore, the reduction of NOx increasing with the height of the secondary air injection point can only be explained by the increase in the importance of the splash zone in NOx formation/reduction reactions, due to the aforementioned characteristically high volatile matter content of biomass.

The results shown in Fig. 5 also confirm that the extent of NOx reduction is higher with the non-woody biomasses due to their higher fuel-N contents. The highest NOx reduction at ca. 30% was achieved when firing straw and miscanthus pellets under AS2 conditions and operating with 10% overall excess air, whereas almost a constant NOx reduction at 26.6% was achieved for peanut shell under AS2 conditions within the whole range of excess air values (10%–50%) used in this work. On the other hand, the effect of air staging in reducing NOx emissions is small with the biomass fuels that have lower fuel-N contents, e.g. the woody biomass fuels. A reduction of NOx was only seen under the AS2 conditions with the industrial wood pellets while no NOx reduction was achieved in any case with domestic wood pellets, which is the biomass fuel with the lowest fuel-N content. This is expected as air staging controls NOx emissions by inhibiting the conversion of fuel-N to NOx and to a smaller extent by reducing thermal-NOx formation [9]. With low fuel-N fuels (e.g. the domestic wood pellets and the industrial wood pellets), the NOx emissions are already low and hence the scope for NOx reductions with air staging is limited.

3.5. Effect of air staging at two different injection points on CO emissions

Fig. 6 shows the effect of excess air on the CO emissions for all of the tested biomass fuels under conditions of without air staging (WAS) and with air staging at two different injection points (AS1 and AS2). The use of air staging has led to a decrease in CO emissions for almost all cases and the reduction in CO emissions is seen to be quite similar for air staging at AS1 and at AS2. As shown in Section 3.3, air staging resulted in an increase in the gas temperatures in the splash zone and freeboard, indicating significant conversion of unburned CO in these sections. In addition, the use of air staging resulted in an increase in the fuel residence time in the primary combustion zone and consequently, this could have contributed to the lowering of the CO emissions [34]. It can also be observed in Fig. 6 that the CO emissions achieved in these experiments were relatively high, within the range of 0.1–0.6%. This is not unusual for biomass BFB combustors as other authors have also reported high CO emissions when burning biomass fuels in their BFB combustors. For example, Khan et al. [19] investigated the combustion of two biomass fuels, demolition wood and pepper plant residue, from an emission viewpoint with a 20 kW_{th} BFB combustor and a $1MW_{th}$ BFB combustor. The CO emissions obtained with the $1MW_{th}$ BFB combustor which has a shallow bed and a smaller freeboard were typically within the range of from

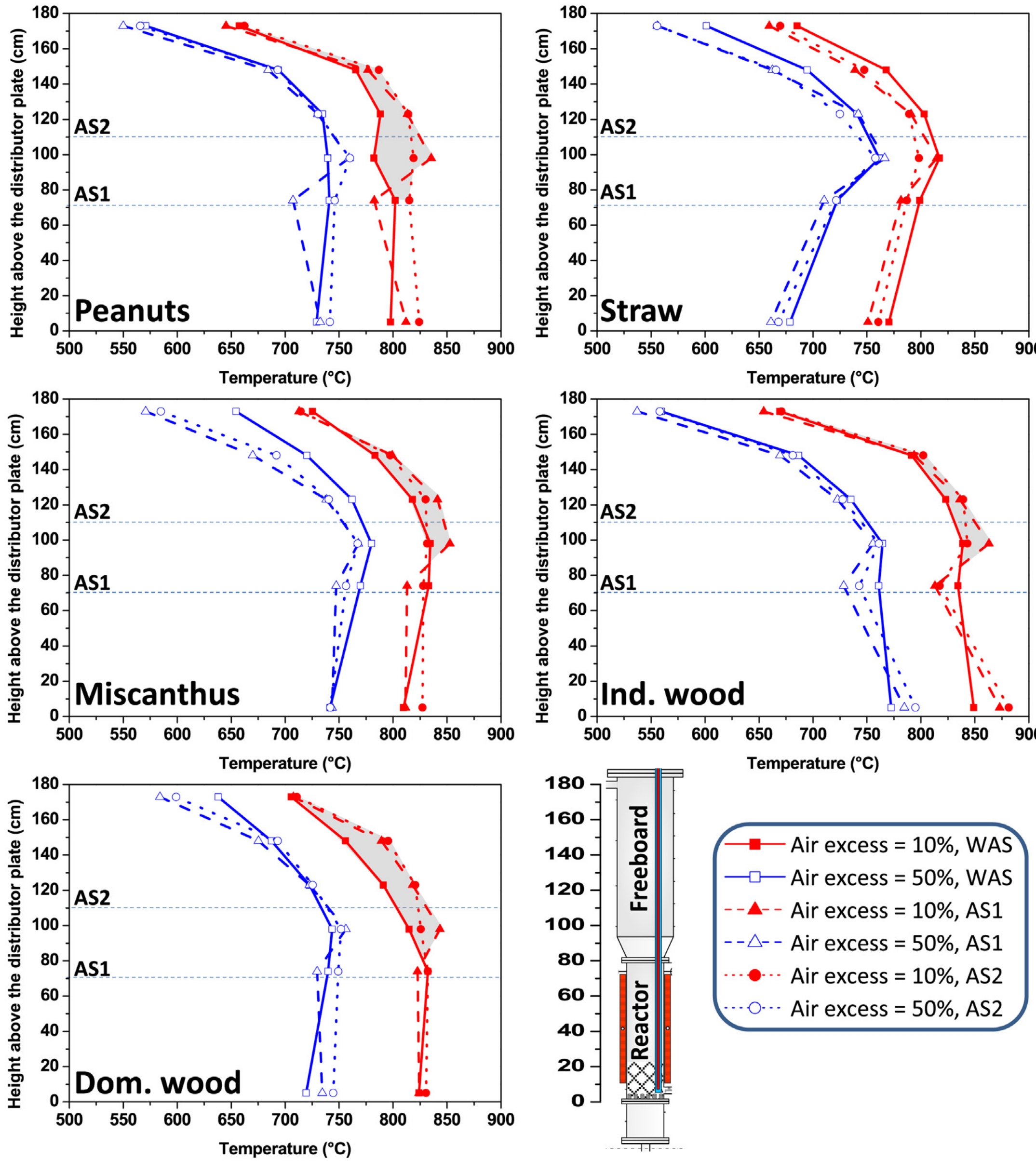

Fig. 4. Temperature profiles along the reactor/freeboard for all biomass fuels.

about 0.1% to well above 1.0%, much higher than the CO emissions of the 20 kW_{th} BFB combustor burning the same kinds of biomass fuels, typically within the range of from 0.01% to less than 0.2%. Okasha et al. [44] carried out an experimental study on staged-air combustion of rice-straw pellets with a jetting-fountain fluidised bed combustor. The CO emissions achieved in this case were between ca. 0.1% and 0.6%, the same range as the one obtained in the present work.

The relatively high CO emissions obtained in this work can be attributed to several factors. Firstly, the cooling probe crossing the freeboard region reduced the gas temperature in the freeboard and therefore inhibited the conversion of CO to CO_2. Secondly, the freeboard region was not high enough as the original design of the BFB combustor was restricted by the available ceiling height at the old laboratory: biomass has a comparatively high volatile content and therefore needs more residence time in the freeboard to completely burn off the volatiles. The results of Khan et al. [19] had confirmed the importance of a longer freeboard region in achieving low CO emissions with biomass combustion. Thirdly, the properties of the biomass pellets, especially the moisture content and the amount of the fine particles in the pellets, could also have affected the combustion efficiency and hence the CO emissions: some of the non-woody biomass fuels, e.g. straw pellets and miscanthus pellets contain more fines than the woody biomass pellets. The fines in the fuels can be easily entrained to the freeboard region, resulting in high CO emissions and the high dispersion of the data shown in Fig. 6 at some cases are believed to be partly resulted from the variations of the fines in different batches of the tested fuels. Finally, the accumulation of the biomass ash on the surfaces of the burning fuel particles could have weakened the oxygen penetration to the combustible part of the particles [34]. Despite of the relatively high CO concentrations achieved at the outlet of the reactor in some cases, the CO emissions obtained in this study at excess air levels higher than ca. 30% under air staging conditions still comply

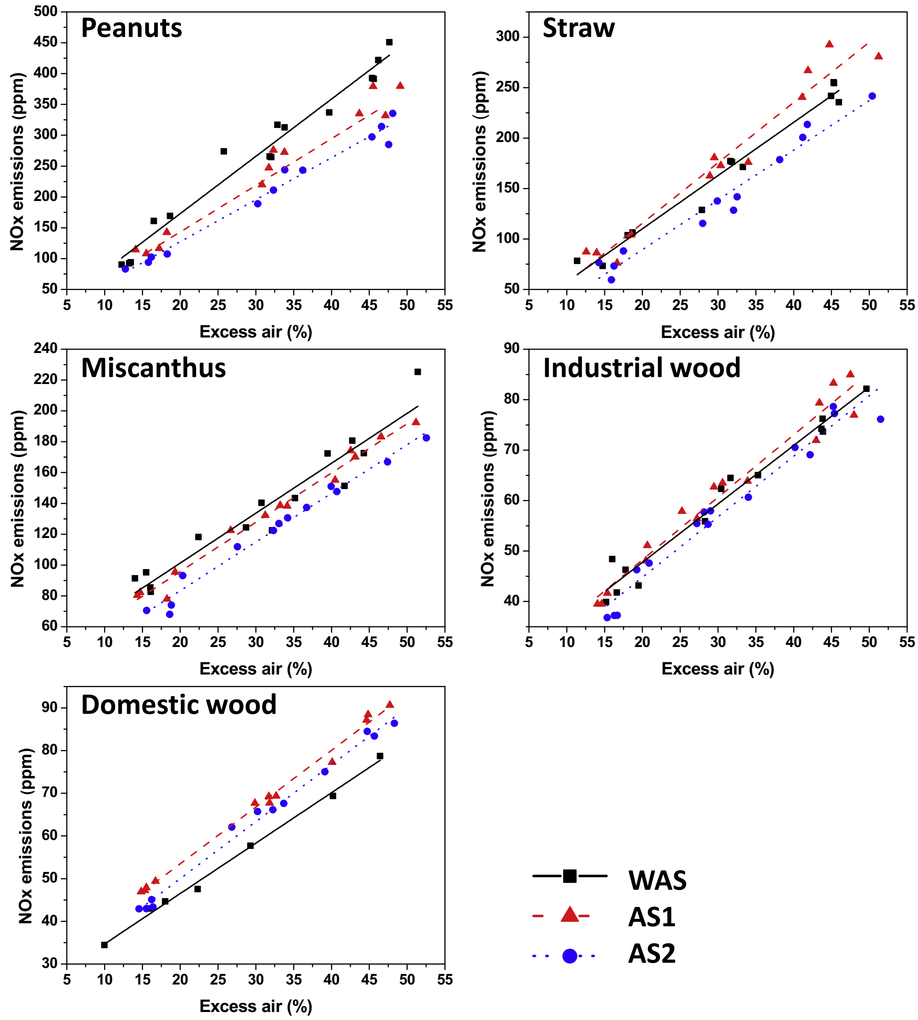

Fig. 5. Effect of excess air on NOx emissions for all of the tested biomass fuels under conditions of without staged air (WAS) and with staged air, introduced from two different locations: 70 cm (AS1) and 110 cm (AS2) from the distribution plate. NOx emissions are expressed as parts per million (ppm) on a dry basis, corrected 6% O_2 in the flue gas.

with the regulations regarding CO emissions for small-scale (<50 kW_{th}) biomass boilers [45]. To further reduce the CO emissions, a new cooling probe will be designed and used in the near future so that it removes heat mainly from the lower part of the reactor (the dense bed region) rather than from the freeboard and splash region which should remain at high temperatures and therefore favour the conversion of CO to CO_2. Test runs without the use of a cooling probe could also be an option if the bed agglomeration and defluidisation can be avoided, for example, by use of alternative bed materials [31].

The observed CO emissions shown in Fig. 6 represents an efficiency loss between ca. 0.6% and 3.9% according to the estimation using Equation (1) [46]:

$$Efficiency\ loss\ due\ to\ CO\ emissions = \frac{\%CO}{\%CO_2 + \%CO} \times 100 \qquad (1)$$

where $\%CO_2$ and $\%CO$ are the concentrations of CO and CO_2 measured at the outlet of the reactor, expressed as vol. % on dry basis. The efficiency loss values due to incomplete combustion obtained here are in the same order as the ones achieved by Ninduangdee and Kuprianov [47] burning palm kernel shell in a fluidised-bed combustor with an air excess in the range of 20–80%.

3.6. Effect of air staging on the efficiency loss due to unburned carbon content (UBC) in fly ash

For this small-scale BFB combustor, there was no removal of bottom bed ash during operation and hence it was not possible to estimate the efficiency loss due to the carbon in the bottom bed ash which is expected to be quite small as a result of high volatile matter contents of the biomass fuels. After each day's operation, the fly ash collected by the cyclone ash pot was weighed and analysed for the carbon content. The efficiency loss due to the unburned carbon in the fly ash was then estimated using the fuel *LHV* (kJ/kg, on as-received basis), the fuel-ash content, *A* (wt.%, on as-received basis), and the unburned carbon content of the fly ash, *UBC* (wt.% on dry basis) according to Equation (2) [20,29]:

$$Efficiency\ loss\ due\ to\ UBC = \frac{32,866}{LHV}\left(\frac{UBC}{100 - UBC}\right)A \qquad (2)$$

Fig. 7a - b show the effects of air staging on the UBC content in the fly ash and on the efficiency loss due to the UBC content in the fly ash for the five biomass fuels tested in this study. As the fly ash

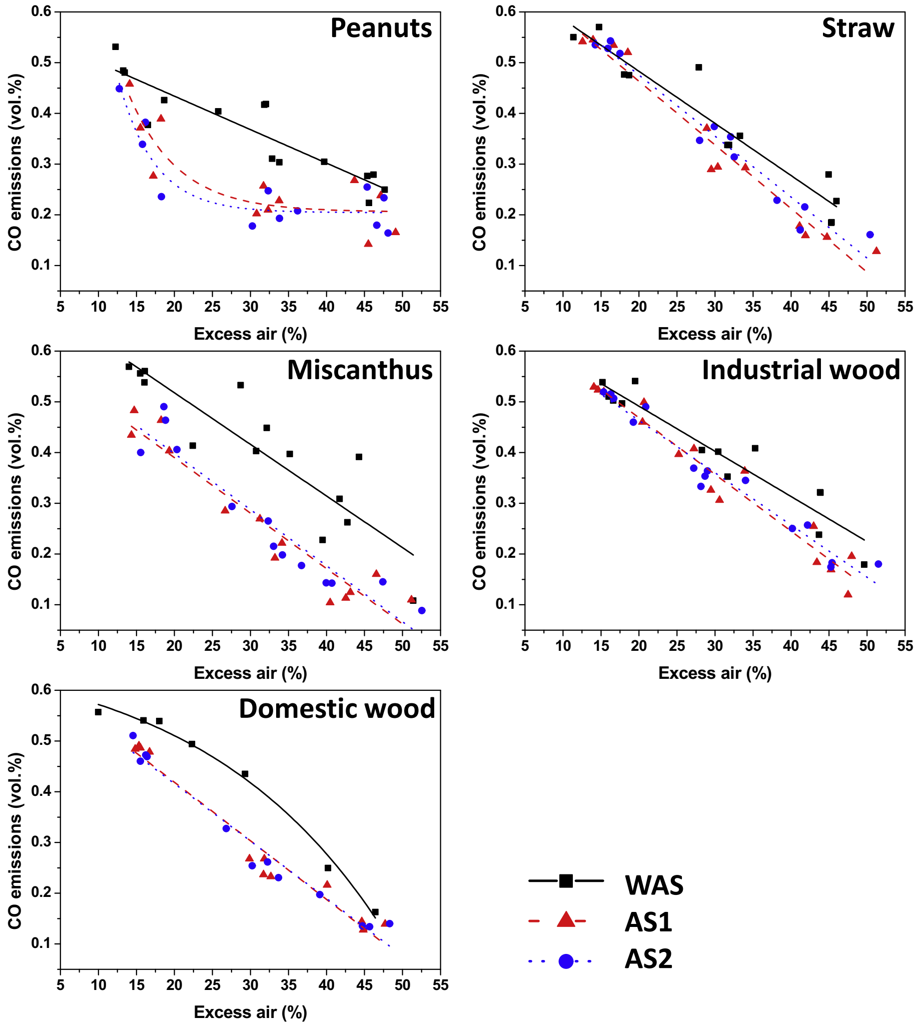

Fig. 6. Effect of excess air on CO emissions for all of the tested biomass fuels under conditions of without air staging (WAS) and with air staging at two different injection points (AS1 - 70 cm and AS2 - 110 cm). CO emissions are expressed as vol. % on a dry basis and corrected to 6% O_2 in the flue gas.

collected at the end of each testing day was resulted from the tests under both air staging conditions (AS1 and AS2), the effect of the secondary air injection location on the UBC content in the fly ash and hence the associated efficiency loss could not be distinguished. As it can be seen in Fig. 7, the use of air staging results in a significant increase of the UBC content in the fly ash, and consequently a higher efficiency loss for all the fuels. This is not unexpected as the use of the secondary air leads to a decrease in the primary air flow rate in order to maintain the total air flow rate constant and this reduces the stoichiometry in the dense bed. A shortage of oxygen in the dense bed lowers the char combustion rate, resulting in a greater concentration of char within the bed. Therefore the char comminution (attrition and fragmentation) rate increases, yielding a greater amount of elutriable fines and carbon loss. Other authors find similar trends [44,48]. The UBC values obtained in this work are in the same order as the ones obtained by Okasha et al. [44] firing rice-straw pellets in a jetting-fountain fluidised bed reactor under air staging conditions. The efficiency loss due to UBC in the fly ash was found to be the highest for straw, which has the highest ash content, among the tested biomass fuels for both conditions of without air staging and with air staging. In general, the efficiency losses due to UBC in the fly ash are expected to be higher for non-woody biomasses, given the higher ash content of these kind of biomasses comparing with woody biomasses.

4. Conclusions

Five different kinds of biomass pellets (peanut shell, straw, miscanthus, domestic wood and industrial wood) were successfully combusted and tested in a 20 kW_{th} bubbling fluidised bed combustor. The effects of the excess air, without air staging and with air staging at different injection heights on the gas emissions (NOx and CO) and temperature profiles were systematically investigated. The main conclusions are:

(1) Higher overall excess air always leads to higher NOx emissions for any of the tested biomass fuels as the combustion condition with higher excess air favours the conversion of fuel-N to NOx and there are less CO and char available in the reactor to promote NOx reductions. NOx emissions depend directly on the fuel-N content – the higher the fuel-N content, the higher the NOx emissions;
(2) As a consequence of the characteristically high volatile matter contents of the biomassfuels, the maximum temperatures are reached above the dense bed in the splash region and/or at the beginning of the freeboard, which suggests that the main combustion reaction takes place in this part of the combustor. Air staging leads to higher temperatures in the splash region and freeboard, especially

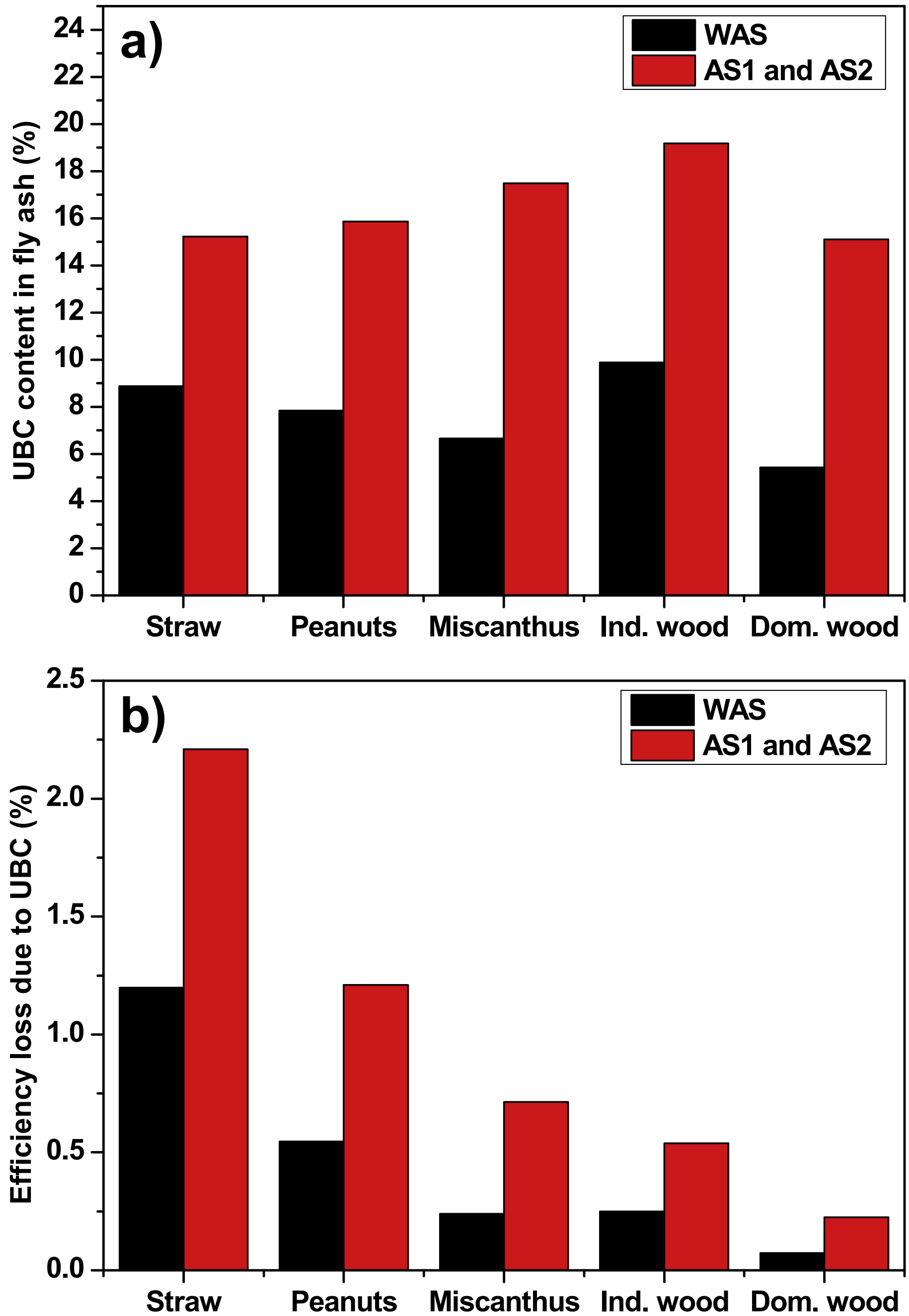

Fig. 7. a) Effect of air staging on the UBC content in the fly ash. b) Effect of air staging on the efficiency loss due to UBC in the fly ash.

at low excess air levels, as a result of additional combustion in the freeboard under air staging conditions.

(3) Air staging can be very effective in reducing NOx emissions (up to 30%) for non-woody biomass fuels which usually have relatively high fuel-N content, especially if the secondary air is injected at the higher level of the BFB combustor and the BFB combustor is operated with a low overall excess air level.

(4) The use of air staging, with the secondary air injected at any of two positions, also leads to lower CO emissions and this is due to the higher gas temperatures in the splash region and freeboard as well as the longer residence time of fuel particles in the primary combustion zone.

(5) However, the use of air staging leads to an increase in the unburned carbon content in the fly ash, resulting in additional efficiency loss.

The present work helps to better understand the combustion and emissions of biomass fuels in BFB combustors, in particular, non-woody biomasses which have great potential as cheap alternatives to high-quality woody biomass for energy supplies and power generation in the future.

Acknowledgment

This work was supported by the UK Engineering and Physical Sciences Research Council [grant number EP/M01536X/1].

Nomenclature

AS1	Air staging, with secondary air injected from 70 cm above the distributor plate
AS2	Air staging, with secondary air injected from 110 cm above the distributor plate
BFB	Bubbling fluidised bed
FBC	Fluidised bed combustion
FC	Fixed carbon
LHV	Low heating value
M	Moisture
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction
UBC	Unburned carbon content
VM	Volatile matter
WAS	Without air staging

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