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Research article

Air staging strategies in biomass combustion-gaseous and particulate emission reduction potentials

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ABSTRACT

Gaseous and particulate emissions have been investigated with different air staging strategies over a wide range of secondary air flow rates. Laboratory scale wood pellet combustor, supplied by an underfeed fuel bed input, is used. The air staging strategies have been employed to study burning rate, temperature in primary and post combustion zones, and NO, CO and PM emissions, taking into account the air to fuel stoichiometric ratio. 50% CO reduction and 9 times less particle mass concentration than non-staged combustion are achieved by deploying a uniform secondary air module in a higher position from the bed. The minimum NO (37% reduction than non-staged) measured in the non-uniform air distribution module at the higher flow rate with lower distance from the fuel bed. The results demonstrate a trade-off between NO and CO, PM emissions but also significant potential for reducing particulate and gaseous emissions by deploying air staging in the pellet combustor.

1. Introduction

The growing awareness and concern over environmental problems associated with fossil fuels have increased the demand for biomass as one of the most accessible alternative energies for the 21st century. Biomass ranks fourth among energy resources, providing >5.4% of world's primary energy supply according to the International Energy Agency [1]. However, inefficient solid biomass combustion may elevate Nitrogen Oxides (NO_x) and Carbon Monoxide (CO) emissions. In addition, burning biomass generally produces high amounts of particulate matter (specifically, aerodynamically fine particles with diameters <1 μm, which have serious side effects on human organs. Accordingly, newly established strategies focus on using well-designed automatic grate biomass burners to achieve higher efficiencies and lower emissions [2].

There is strong evidence that the combustion of biomass depends on the air supply rate [3–5] and, in turn, the primary air effect on burning rate, ignition rates and peak temperature (the key parameters of combustion) in fixed-bed combustion. A general wood conversion rate line was proposed by Porteiro et al. [6] that takes into account the burning rate and the air-to-fuel stoichiometric ratio (λ) by dividing the combustion into two major parts: fuel rich (unburned hydrocarbon) and fuel lean (higher oxygen concentration). Yang et al. [7] proposed the sub-stoichiometric ratio of primary air ($\lambda_p < 1$) in large-scale grate burners to achieve similar efficiency with a higher primary air flow rate.

In recent years, numerous techniques have been applied to systematically enhance air staging strategies to yield higher combustion efficiency (about 55–70% for conventional stoves and 80–90% for high technology combustion stoves) and achieve higher performance for large-scale pellet boilers and waste incinerators [8,9]. Biedermann et al. [10] summarised air staging results for different aspects of air staging across various studies. Wiinikka and Gebart [11,12] concluded that an equal distribution of primary and secondary air flow rates reduced total emissions in a laboratory-scale, overfeed bed reactor.

1.1. Particulate emissions (PM) and CO

Consecutive secondary air injection in the different underfeed reactors was investigated by Nussbaumer [13]. The results revealed that lower concentrations of PM and CO were achievable though higher temperature and good mixing of excess air in the secondary air section. Hence, a self-adjustable excess air control system was recommended to ensure an optimum excess air ratio. Jonhansson et al. [14] showed that imperfect combustor design and unsatisfactory excess air ratio in different upper feed stockers and small heating burners resulted in higher particle mass concentrations. Specifically, the secondary air injection angle and higher residence time influenced temperature in the post combustion zone and associated total particle emissions (Wiinikka et al. [15]). Tissari et al. [16,17] indicated that a closed fire box and inappropriate air intake size in masonry heaters caused higher temperatures and fast pyrolysis, which led to high particle and gas emissions. Hence, good mixing and air distribution decrease PM emissions and facilitate

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very efficient combustion. The influences of temperature, PM and air staging on softwood pellet combustion were studied by Pettersson et al. [18]. A combination of sufficiently high temperature (in the primary zone), air rich condition and good mixing of air and flue gas led to a near complete combustion condition, whereas residence time in the post combustion zone had only a minor influence. Lamberg et al. [19] showed that sufficient primary and secondary air flow rates reduced PM and CO emissions by enhancing mixing rate in the post combustion zone; therefore the ideal ratio of primary to secondary air should be sustained for complete combustion. Orasche et al. [20] concluded that a lower air temperature contributed to higher PM and CO concentration in different small scale grate combustors.

1.2. NO_x emission

In general, the combustion of wood leads to far higher emission of NO_X (collective term for mainly >90% NO, and NO_2, N_2O) than oil or gas combustion [21]. Formation of NO_x occurs through four main mechanisms: 1) Thermal, 2) Prompt, 3) Nitrous oxide and 4) Fuel-N conversion mechanisms. Recent studies emphasised that the first three mechanisms are less important in biomass combustion than Fuel-N conversion due to high temperature (<1400 °C) (1), long residence time and less CH radical production (2), and very fuel lean combustion with low temperature conditions and higher pressure (3) [22]. The most influential parameters for NO_x formation and reduction are: temperature [8], residence time [13,23], primary air [24,25], excess air ratio [26], fuel N-content and mixing ratio [26–28] and the number of air staging [29]. Several techniques are used to reduce NO_x level in biomass combustion: fuel staging [25], air staging [19,23], CS (combined staging) [30], selective non-catalytic reduction (SNCR) [31], flue gas recirculation (FGR) [32,33] and deflector sheet application [34].

Reduction of NO_x (50–80%) was reported by Nussbaumer et al. [13] to have occurred due to air staging, residence time and the primary excess air ratio. However, higher excess air levels may reduce combustion efficiency by reducing combustion temperature leading to higher PM and CO. Saastamoinen et al. [35] indicated that lower NO emissions were achievable at lower primary air flow rates because of the longer gas residence time. In fact, lower oxygen concentration will cause NO to act as an oxidant for CO, CH_4, HCN and NH_3 in the reduction zone, hence reducing the nitrogen in NO and NH_3 to molecular nitrogen [13, 36]. Large NO_x reduction potential was reported by Houshfar et al. [25] through air staging in an upper feed grate reactor with an optimum primary excess air ratio between 0.8 and 0.95 and higher total excess air ratio ($\lambda_T \sim 1.6 > 1$) for a fixed reactor temperature (850 °C). Carroll et al. [33] found an ideal ratio of primary air flow rate and kept a constant temperature in the primary combustion zone via flow gas recirculation; this resulted in remarkable NO_x and 30% particle emission reductions in a grate biomass boiler. Table 1.1 shows a summary of some relevant research regarding to air staging strategies.

Despite the existence of excellent experimental studies on numerous aspects of air staging, the relationship between the abovementioned emissions and geometrical aspects such as secondary air configuration and its distance from the bed require further investigations by taking into consideration air staging strategies. In this study, air staging is investigated by adjusting two different secondary air modules at two distances from the bed (four combinations). Detailed analysis of temperatures in primary and post combustion zones, burning rate, PM, NO, CO and CO_2 emissions over a wide range of secondary air flow rates have been performed on a fixed-bed laboratory scale pellet combustor.

2. Laboratory scale reactor

The fixed bed lab-scale reactor consists of five main zones: I-Plenum, II-Primary combustion (where the initial combustion take place), III-Secondary air inlet, IV-Post combustion (where the produced volatiles in Zone II are combusted), and V-chimney (Fig. 2.1). The 15 kW non-isolated reactor is made from 310 stainless steel with a square cross-sectional area of sides 120 mm long. The overall height of the reactor is 1500 mm and all walls of the reactor are exposed to ambient conditions. Primary air is supplied under an inclined grate to guarantee homogeneous air distribution in the reactor. The stainless steel grate (120 mm × 128 mm) consisting of 120 (4 mm diameter) holes that represents a 40% open area is installed at an angle of 25 degrees to prevent crushing the pellets by the screw feeder during combustion. The hopper (pellet fuel storage) is directly connected to a screw feeder system and the fuel is fed into the combustion chamber (zone II) by a screw conveyor from below and is transported upward on the grate. The ash deposits collected from the tests are then removed through a blind cap located at the bottom of the plenum. The hopper is suspended by four chains attached to an overhead beam via an accurate load cell (± 10 g resolution) to monitor the mass loss of the fuel bed. Primary air flow rate is fed from an inlet located at Zone I and secondary air is added above the grate by a port placed in Zone III as shown in Fig. 2.1. Primary and secondary air sources are provided by two variable frequency drive centrifugal fans (Schneider Electric, model: Altivar 31). Two high precise digital mass flow controllers (Van Putten Instruments, model: VPF.R200.100, accuracy: 0.5% full-scale) are used to control the supply air. The flue gas temperature in the reactor is measured continuously by fifteen (3 mm) thermocouples (Type N), coated by a Nicrobel sheathed thermocouples (make: TC measurement, model: 2I-Nickel-Silicon-Magnesium). Each thermocouple has a sheath of 300 mm length and outer diameter of 3 mm. All temperatures reported in the freeboard (zone II, IV) have either been measured by positioning the thermocouples at the centre of combustor (r = 60 mm from the wall). The thermocouple temperature

Table 1.1
Summary of some related research concerning air staging strategies.

NO_x	CO	CO_2	O_2	PM	Residence time	S.A configuration	S.A distance	Post comb. temperature	Reference
✓	✓	✗	✓	✗	✗	✓	✗	✗	[8]
✗	✗	✗	✗	✓	✗	✓	✗	✗	[11]
✗	✓	✗	✗	✓	✗	✓	✗	✗	[15]
✓	✓	✗	✓	✓	✓	✓	✗	✓	[13,37]
✗	✓	✓	✓	✓	✗	✓	✓	✗	[16]
✓	✓	✗	✗	✓	✗	✓	✗	✗	[14]
✓	✓	✗	✓	✓	✓	✗	✗	✓[b]	[19]
✗	✓	✗	✗	✓	✓	✓	✗	✓[b]	[18]
✓	✓	✗	✗	✓	✗	✗	✗	✗	[20]
✓	✓	✓	✓	✗	✓	✗	✗	✗	[25]
✓	✗	✗	✗	✗	✓	✗	✗	✓[b]	[26]
✓	✗	✓	✓	✗	✓	✗	✗	✓[b]	[32][a]
✓	✓	✗	✓	✓	✓	✗	✗	✓[b]	[33][a]

[a] CS (combined staging): air staging and flue gas recirculation (FGR).
[b] The temperature is held constant between 800 and 1000 °C.