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Experimental investigation on the air excess and air displacement influence on early stage and complete combustion gaseous emissions of a small scale fixed bed biomass boiler

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HIGHLIGHTS

- Experimental data about exhaust gas and early combustion stage volatiles are provided.
- The spatial distribution of the species is strictly correlated with the primary mass flow air.
- Emissions and temperatures are investigated for various air excess and air displacement values.

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ABSTRACT

The world energy demand growth is more and more supplied by renewable energy sources. In this scenario, biomass has a key role in both heat and power generation. Particularly, biomass combustion can be used in small size micro and distributed generation systems, or in smart grids together with wind and solar energy where a programmable energy source is necessary to keep the electric grid stable. In this paper, a small size 140 kWth biomass fixed bed boiler of the University of Pisa, located at the Biomass to Energy Inter-University Research Centre (CRIBE), was studied experimentally to characterize the biomass combustion process. Emissions of NO_x, O_2, CO_2 and CO, together with the temperature data, were measured in the flue gases. Moreover, the spatial distribution of volatile products from the fixed bed surface, such as H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2, together with temperature data, was studied in the early combustion stage. The parametric variation of the feed air flow and its effect on the emissions and performances was also investigated. The results indicate that the primary air mainly affects the volatiles distribution on the biomass combustion surface. Therefore, the CO emission was minimized at values of 0.03%vol with an air excess equal to 2 and a 0.06 secondary to primary air mass flow ratio.

1. Introduction

During the last decades, the global primary energy demand continued to rise significantly and a larger share of the world population has now access to electricity and modern heating and cooling systems. In order to contain global warming and reduce fossil fuel resources, the use of renewable energy sources appears to be mandatory. In this scenario, the development of smart grid systems and the integration between solar, wind and biomass power plants play a key role for future energy production [1,2]. Particularly, systems based on biomass combustion are interesting for both heat and power generation, and, being programmable, may improve the flexibility of the energy mix. Moreover, small scale plants based on this technology are convenient for distributed and micro generation [3,4], and can be employed in cogeneration and ORC applications [5–8]. Nevertheless, the use of these systems is limited by the biomass feedstock availability, strongly linked to costs, and the variability of the fuel characteristics and composition. A correct management and planning can reduce the problem of fuel availability, but the variability of biomass characteristics (e.g. granulometry, ultimate and proximate analysis, lignin, cellulose and hemicellulose content) affect the thermal performance and the pollutant emissions. During the years, the studies about biomass use covered

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Nomenclature

Abbreviations	Description
A	casing surface
Cp	specific heat at constant pressure
d_{50}	diameter at 50% of the cumulative distribution
d_{max}	maximum diameter of the cumulative distribution
F	view factor
k	thermal Conductivity
LHV	lower heating value of the fuel
m	mass flow
Q_c	casing heat loss
Q_s	sensible heat loss
Q_u	unburnt biomass heat loss
T	temperature
U	global heat transfer coefficient
Y	mass fraction
α	air to fuel ratio
α_{st}	stoichiometric air to fuel ratio
ε	air excess
ε_r	radiative emissivity
η	boiler thermal efficiency
λ	secondary to primary air flow ratio
σ_r	Stefan–Boltzmann constant

Subscripts	Description
a	air
b	biomass
C	Center
e	exhaust gases
in	inlet
L	Left
M	Middle
o	oil
out	outlet
p	primary
R	Right
s	secondary
S	Side
tot	total
u	unburnt
w	wall

many aspects of this resource: from the physical and chemical characterization, to the experimental campaigns for the combustion performances investigation, and many papers were published in the recent literature.

Wielgosinski et al. [9] studied the NOx, CO and TOC (i.e. Total Organic Carbon) emissions of different biomass in a laboratory scale electric furnace, and compared the results with those from hard coal. They found that biomass combustion must be improved by both thermal management and feeding air flow rate optimization, in order to reduce the emissions to the fossil fuels levels. Al-Shemmeri et al. [10] conducted tests in laboratory scale stove by using miscantus, straw, rice husk pellets, saw dust and other wood chips. The authors highlighted the strong effect of the fuel moisture on temperature and combustion products. Moreover, they found that the system performance can be improved by a proper feeding air displacement and staging. Other authors [11–13] investigated the main kinetic properties of biomass combustion using TGA (Thermo Gravimetric Analysis) and laboratory scale facilities.

In the literature, many examples of experimental facilities are provided; and the effect of the air displacement and air excess are investigated with respect to the emission products.

For instance, Serrano et al. [14] studied the pollutant emissions from a 50 kW domestic stove, by using pinus halepensis and pinaster woodchips as fuel. They found the flue gas temperature is raised by the increase of secondary air flow growth, while the carbon monoxide content is decreased in the same condition. A similar apparatus was employed by Lamberg et al. [15], who varied the power between 7 and 25 kW and highlighted the air displacement as the main emission composition control parameter.

Moreover, Dias et al. [16] used a domestic 13 kW stove and they found a strong relation between the flue gas oxygen, carbon monoxide and nitrogen oxides content. Particularly, a linear correlation was detected between the O_2 and the NOx in the exhaust composition. A higher power range system was employed by Zhang et al. [17] that used a 320 kW moving grate boiler to study the air excess and air displacement effect on the combustion behaviour; and a strong relation of the emissions and the air excess was highlighted. Other authors, such as Fournel et al. [18] investigated the combustion and emissions of a 30 kW multi fuel boiler, employing different types of biomass (i.e. short rotation willow, miscanthus, switchgrass and reed canary grass), shapes and harvesting seasons. Although a large variation of the emissions was observed due to the combustion of different fuel and to varying combustion conditions, CO concentration in the flue gases was found to be strongly related to the air excess. Particularly, an air excess increase induced higher carbon monoxide emissions and lower bed temperatures. Similar results were achieved by Roy et al. [19] who proposed a similar correlation between air excess and CO in a 32 kW pellet boiler. They also stated that the thermal input, the overall efficiency and the thermal losses, are strongly dependent on the excess oxygen in the flue gases. Carvalho et al. [20] used an air excess control strategy to minimize CO emissions from the 15 kW pellet boiler they studied. It was also noticed that carbon monoxide emissions were related to the temperature of the combustion chamber; hence, it could be controlled by varying the feeding air flow rate.

From the considered works, it appears clear that the air excess and the air displacement are important for the chemical and thermal behaviour of the biomass combustion systems. However, the authors do not always agree about the main pollutant and control parameters correlations. This fact highlights that slightly different systems can behave with quite different patterns of emission, and that it is important to focus new studies and research activities on the earliest combustion stages.

For instance, Buchmayr et al. [21] investigated the surface of a 50 kW woodchips biomass furnace, studied the volatiles from the biomass combustion surface, and found that the air displacement plays a key role in the bed zone temperatures. Also Gehrig et al. [22] found that the temperature of the combustion bed has a direct influence on the spatial distribution of the main pollutant emitted. They used a cooling device to control the heat release of the burning biomass and reduced the emission production spatial difference by reducing the combustion temperature. They also stated that a similar effect could be achieved by means of a secondary air distribution system.

In the literature, few data are available about the early stage products, even if they could be interesting for model development and validation purpose [23]. In fact, the use of fuel modelling as a tool to investigate the combustion in computational fluid dynamic codes is a common practice [24–26], especially if this leads to significant reductions of computational efforts of the performed simulations. On the other hand, the use of numerical models for biomass combustion requires the coupling between the solid fuel and the gas transport phase, and their interaction represents a critical point to describe these problems in a affordable way [27,28], especially when a complete early stage combustion validation is strictly required.

Most of the literature results are carried out in laboratory scale or