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Relationship between fuel quality and gaseous and particulate matter emissions in a domestic pellet-fired boiler

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HIGHLIGHTS

- Relationship between fuel quality and gaseous and PM emissions.
- Pellets examined generally fulfilled the requirements for non-industrial pellets.
- Gaseous and PM emissions are significantly affected by the fuel type.
- PM emissions are dominated by PM2.5 and affected by the fuel ash composition.

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ABSTRACT

The general purpose of this work is to evaluate the relationship between the fuel quality and the gaseous and particulate matter (PM) emissions in a domestic boiler fired with five different types of pellets, namely, two commercial pellets from pine residues, commercial pellets from cork residues, and in-house made pellets from olive wood and olive pruning residues. Initially, to evaluate if the pellets fulfill the requirements established in the European standards, a detailed physical and chemical characterization of the five types of pellets was performed. Subsequently, to examine the impact on pollutant emissions of the fuel type, all pellets were burned in the domestic boiler, each for three boiler thermal loads, and their gaseous and PM emissions were measured. Finally, to better understand the impact of the fuel ash composition on PM emissions, a number of selected PM samples were morphologically and chemically characterized. All pellets fulfilled the physical and mechanical requirements for non-industrial pellets, except in the case of one of the commercial pine pellets, which showed bulk density and durability values lower than the limits established in the European standard. In addition, pellets made from olive pruning showed higher nitrogen and sulfur contents, and cork pellets showed significantly higher sulfur content than those allowed for their use in domestic appliances by the European standard. Gaseous and PM emissions are significantly affected by the fuel type. The high CO emissions of the olive based pellets were attributed to their high particle densities and high length to diameter ratios, while the high NO_x emissions of the olive pruning pellets were attributed to its very high nitrogen content. Among the agro-pellets, the cork pellets originated PM emissions lower than those from the olive wood pellets and much lower than those from the olive pruning pellets. All PM emissions were dominated by particles with sizes below 2.5 μm, which are significantly affected by the fuel ash composition, namely by the amount of volatile inorganic elements K and Na.

1. Introduction

Biomass is an abundant renewable energy source, and its use in form of pellets in small-scale combustion systems is becoming a common source of thermal energy production [1–7]. This is due to the fact that pellets present characteristics such as their homogeneity and high energy density that improve the efficiency of the appliance and facilitates its automatic operation.

Currently, the main biomass fuels used in small-scale combustion systems are wood derived fuels. The growing demand of these biomass fuels may lead to an unbearable pressure on the forest, since an increased demand can drive to unsustainable levels of harvesting, with negative consequences for biodiversity, soil, and water conservation [8]. In order to alleviate this pressure, while increasing the use of biomass in small-scale combustion systems and thereby reduce CO_2 emissions, it is necessary to increase the use of alternative biomass fuels considered in the biomass

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classification made by the European standard EN 14961-1 [9]. Moreover, previous studies [10–17] have shown that some non-conventional raw materials have a considerable potential to be used in domestic pellet-fired boilers.

In countries like Portugal, Spain and other Mediterranean areas, the cork and olive oil sectors generate large amounts of residues that can be used as fuel in domestic heating systems. However, the European standard EN 14961-2 [9] establishes quality specifications for non-industrial pellets that those from residual biomass generally do not easily fulfill because of the specific characteristics of the raw material. In light of this, more research on these biomass sources is needed to investigate their quality as fuels and the emissions generated during their combustion.

Low-quality pellets can cause operational problems in combustion systems, including undesired effects in the equipments such as slagging, fouling or corrosion, and may originate substantial amounts of gaseous and particulate matter (PM) emissions [10–18]. On the gaseous emissions side, the type of pellet has a significant impact on the emissions of CO, hydrocarbons (HC) and NO_x, although the performance of the boiler is not significantly affected [15–17,19]. On the PM emissions side, it has been observed that in the case of combustion-related particles, the fine PM fractions (PM1 or PM2.5) are especially harmful to the human health [20,21] and, indeed, it is well known that residential biomass combustion generates high amounts of fine PM [22–24]. It is well established [25–34] that there are two main primary sources for PM formation in biomass combustion: (i) incomplete combustion, which originates soot and unburned char; and (ii) the inorganic matter that constitutes the ash content of the biomass. Recent studies by Wiinikka [26] and Sippula [27] on PM emissions from a small-scale laboratory reactor and from several types of reactors, respectively, showed that inorganic PM emissions were correlated with both the fuel ash content and composition. Very recently, Verma et al. [15,31,32] performed extensive studies in a small-scale pellet-fired boiler that showed that for top-feed pellet-fired boilers the total PM emissions can be dominated by elemental carbon due to disturbances in the fuel bed. Nonetheless, Verma et al. [15,31,32] concluded that PM emissions are significantly affected by the type of biomass fuel. Interestingly, these authors observed that biomass fuels with higher Si content in the ashes produced the lowest total PM emissions.

The importance of studying pellets made from cork and olive residues cannot be overemphasized owing to their high potential in the Mediterranean areas, as discussed earlier. Against this background, the general purpose of this study is to evaluate the relationship between the fuel quality and the gaseous and PM emissions in a domestic boiler fired with five types of pellets namely, two commercial pellets from pine residues, commercial pellets from cork residues, and in-house made pellets from olive wood and olive pruning residues. Initially, to evaluate if the pellets fulfill the requirements established in the European standards, a detailed physical and chemical characterization of the five types of pellets was performed. Subsequently, to examine the impact on pollutant emissions of the fuel type, all pellets were burned in the domestic boiler, each for three boiler thermal loads, and their gaseous and PM emissions were measured. Finally, to better understand the impact of the fuel ash composition on PM emissions, a number of selected PM samples were morphologically and chemically characterized.

2. Materials and methods

2.1. Pellet fuels

Five types of 6 mm diameter pellets were examined in this study, namely, pellets of two types of pine, cork, olive wood and olive pruning. The pellets of pine residues are currently manufactured and commercialized in Portugal and Spain, while the pellets of cork residues are presently manufactured and commercialized in Portugal. The olive wood and olive pruning residues were obtained from an olive grove near Granada (Spain). The olive wood residues were collected in logs and the olive pruning residues were composed by leaves and small branches that were harvested as a whole, both in March 2012.

The pellets of olive wood and olive pruning residues were made at the University of Granada in an existing pilot-scale pelletizer (KAHL 14-175), with a production capacity of 50 kg/h. Initially, the raw materials (olive wood and olive pruning residues) were pulverized down to particle sizes smaller than 5 mm with the aid of a hammer mill (Retsch MM301). Subsequently, a number of tests were made under different operating conditions (initial moisture content, type of die and pelletization temperature) in order to adequate the pelletization process to the raw material to be pelletized. The pellets of olive wood were produced with an initial moisture content of 11%, a flat die of 6 mm of diameter and 24 mm compression length and a pelletization temperature within the range of 60–90 °C. The olive pruning pellets were made at the same pelletization temperature range, but the initial moisture content of the raw material was 9% and the compression length of the die was 20 mm.

Representative samples of each type of pellets were obtained with the aid of sample splitters. Table 1 summarizes the pellet quality parameters studied and the methods used. Each analysis was repeated three times so that the values reported in Section 3 represent mean values of the data obtained.

2.2. Experimental set-up for the combustion tests

The present combustion tests were carried in a domestic top-feed pellet-fired boiler with a maximum thermal capacity of 22 kW, with forced draught. A detailed description of the boiler is available elsewhere [33,34]. Fig. 1 shows a schematic of the experimental set-up. The pellets consumption rate is regulated by the boiler load and is measured with the aid of a loss-in-weight technique, for which the boiler is mounted on a weighbridge. The heat generated by combustion is transferred to an inner water circuit and it is dissipated through a plate heat exchanger with the aid of an external water circuit. The water flow rate circulating in the inner circuit of the boiler was measured with a rotameter and the inlet and outlet temperatures were measured with thermocouples type K, T1 and T2 in Fig. 1, respectively. The temperature of the flue-gas was also measured with a thermocouple type K, T3 in Fig. 1.

2.3. Gaseous and particulate matter emission measurements

Flue-gas was sampled for measurements of the gaseous pollutant concentrations with the aid of a stainless-steel water-cooled probe, placed at the centerline of the exhaust duct of the boiler, and following the standardized measurement methods described in the European technical specification CEN/TS 15883 [45]. The analytical instrumentation included a magnetic pressure analyzer for O_2 measurements, a non-dispersive infrared gas analyzer for CO and CO_2 measurements, a flame ionization detector for HC measurements and a chemiluminescent analyzer for NO_x measurements. Zero and span gas calibrations with standard mixtures were performed before and after each measurement session. At the boiler exit, probe effects were negligible and errors arose mainly from quenching of chemical reactions, which was found to be adequate. The analogue outputs of the analyzers were transmitted via an A/D board to a computer where the signals were processed and the mean values calculated. The values were aver-