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Characterization of operating conditions of two residential wood combustion appliances

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ABSTRACT

This work presents the main physical characteristics and operating conditions of a fireplace and a stove commonly used in Portugal for domestic heating based on biomass combustion. The fuel used was wood from pine (softwood) and eucalyptus (hardwood). The general trend during the batch combustion of wood logs was characterized by three main periods: i) a first period of fuel heating followed by fuel drying and initial steps of devolatilization without the existence of a visible flame, ii) a second period characterized by devolatilization, ignition, combustion of volatiles and char, during which a vigorous flame is observed, and iii) a third period, mainly identified by the combustion of the char, during which there are only localized small visible flames over the char particles. Each of these periods is characterized by specific fuel consumption rate, flue gas temperature and flue gas composition. The main differences between the wood combustion conditions in the fireplace and in the stove include: i) a lower flue gas temperature in the fireplace, ii) a higher combustion flue gas flow rate in the fireplace, iii) a higher rate of fuel consumption in the stove, and iv) higher CO, total hydrocarbon and particle emission factors during the combustion of wood in the fireplace. Differences between hardwood and softwood combustion were also pointed out.

1. Introduction

Wood is commonly used worldwide in residential combustion for heating. Because it is a renewable energy source, its use is recommended aiming to reduce dependence on fossil fuels. However, wood combustion is considered a source of air pollutants with significant environmental and health impacts [1–7]. In the last years, increasing attention has been focused on biomass burning emissions, particularly from wildfires, prescribed fires and agricultural burning [8–13]. However, an important fraction of all biomass combustion occurs in domestic stoves and fireplaces that, although of small scale, are used in considerable number, potentially emitting large amounts of particles and gases [14–19]. Puxbaum et al. [20] argued that emissions from residential wood combustion could be responsible for up to 70% of the organic particulate matter in the atmosphere of European rural locations in winter.

The stove design, operating conditions, combustion conditions (e.g. amount of excess air) and the species of wood and their characteristics are factors with a foremost influence on pollutant emissions [21–27]. Incomplete combustion is among the main problems in domestic equipments, not only affecting local air quality, but also exerting influence at global level because of the emission of greenhouse gases [18]. Improved stoves offer the potential to increase the efficiency of fuel conversion, decrease the negative impacts on public health and reduce adverse environmental effects [28]. In addition, during the last few years there was an effort to improve both the energy and environmental performance of residential combustion equipments through the establishment of guidelines and standards at national and international levels [29,30].

In Portugal, fireplaces and wood stoves are very common for space heating at homes; it has been estimated that 37% of the houses in this country are using these domestic devices, with a 43% of the total using fireplaces [31]. Stoves represent about 24% of the total number of appliances (stoves with similar power output and efficiency level, non-catalytic, as the one of this study) [31]. Wood fuels have distinct characteristics worldwide and that influences the performance of combustion equipments. An inventory carried out in 2010 revealed that about 2 Mt of wood are annually used in Portugal for heating and cooking purposes [31]. Previous studies have been focused on the estimation of emission factors of particulate matter emitted from the combustion of different wood species and briquettes in these Portuguese appliances (stoves and fireplaces) [15,16,31,32], as well as in the assessment of their mutagenic potential [33]. Whereas there is information about the operating conditions and flue gas emissions of pellet stoves [29,30,34–38], the scientific information about the operating conditions and flue gas composition of Portuguese fireplaces and wood stoves is scarce [39, 40]. Improving knowledge on operating conditions of these heating equipments and on composition of flue gas is an important challenge

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considering the achievement of efficient, economic and environmental compatible combustion, also offering the possibility of identification of innovation opportunities.

There are an important number of published studies dealing with domestic wood stoves, focused on some types of biomass ovens, cookers often including pellets [41–48], but working at different loads and modes of operation compared to those presented in this work. This study presents a characterization of the main physical characteristics, operation conditions and flue gas composition of a wood stove and a fireplace, run in batch mode, commonly used in Portuguese households for heating purposes. Two different types of biofuels were used, allowing the establishment of differences between the combustion of softwood and hardwood. Due to the use of these fuels and these residential wood combustion devices in Southern Europe, the results obtained can be of special interest in the Mediterranean region.

2. Material and methods

2.1. Fuel characteristics

Wood from two typical Portuguese tree species was used as fuel: maritime pine (*Pinus pinaster*; softwood) and eucalyptus (*Eucalyptus globulus*; hardwood). They are commonly used as fuel in domestic devices for heating purposes in Portugal [16]. Fuel characteristics (elemental analysis, moisture and ash) are presented in Table 1. The determination of ash and moisture contents was performed in accordance with CEN/TS 14775 and CEN 14774-3, respectively. The elemental analysis was carried out in an external laboratory. The wood was cut into logs of 0.3 to 0.4 m in length. Four logs with a total weight of around 1.7 to 2.0 kg were burned during each cycle. These conditions were selected in order to simulate a typical batch load in domestic devices in Portugal.

2.2. Experimental installation

Two different equipments commonly used in Portugal for domestic heating (air heating) purposes were used in this work (Fig. 1): i) a wood stove (model Sahara) manufactured by the Portuguese company Solzaima [49] and ii) a traditional Portuguese brick open fireplace.

The stove (Fig. 1a) is made in stainless steel and has a cast iron front panel and grate. The volume of the combustion chamber is around 0.09 m^3, corresponding to 0.44 m height, 0.59 m width and 0.36 m depth. It is operated manually in batch mode with handheld control of combustion air. The combustion air enters the combustion chamber throughout a cylindrical structure/tube of 6 cm in diameter, located beneath the door (see Fig. 1), and flows throughout the grate and biomass fixed bed. An air flow meter (Kurz, Model: 500-2.0-P 40) measures the air flue rate entering in the combustion chamber (A in Fig. 1). Furthermore, this cylindrical device supports the hopper for collecting the bottom ashes, located below the grate of the stove.

The traditional fireplace (Fig. 1b) is made of bricks and cement. It has a combustion chamber with a volume of around 0.15 m^3, corresponding to 0.50 m height, 0.70 m width and 0.42 m depth. There is no device for regulating the combustion air flow and no hopper for ash collection below the grate. The air enters the combustion chamber throughout all the front opening of the fireplace and flows below and above the fixed bed of biomass.

In both equipments the driving force for the air entering the combustion chamber is natural convection resulting from the up flowing column of hot combustion flue gases throughout the vertical chimney. The wood stove heats the room air by a combination of radiation, natural and forced convection, whereas the fireplace heats the room air by a combination of radiation and natural convection.

Both devices are equipped with a vertical exhaust duct (chimney) with 0.20 m internal diameter and 3.3 m or 2.7 m height for the stove and fireplace, respectively, in order to have the chimney exit at the same height. In the case of the stove, the exhaust duct was thermally insulated (with Cerablanket, 128 kg m^{-3}, 0.025 m, 0.23 W m^{-1} K^{-1}) in the first 1 m above the stove exit, due to operational safety reasons.

A fixed grate supports the logs under combustion. A weight sensor (load cell DSEUROPE Model 535QD-A5) was connected to the grate in the wood stove and in the fireplace (B in Fig. 1) with the objective of continuous monitoring the weight of fuel in the burning fixed bed. The continuous monitoring of the air flow rate entering the combustion chamber is possible only in the stove by using a mass flow meter. Since, in the fireplace, the combustion air cannot be controlled, a Pitot tube (Testo AG 808) and a K-type thermocouple were used to monitor the gas flow at the exit of the chimney.

Both appliances were integrated in an experimental infrastructure (Fig. 1) that permits the continuous control and monitoring of the reactive system.

Temperature was monitored continuously using several K-type thermocouples at different locations, namely, i) in the stove at the central region of the surface of the grate (i.e., under the fixed bed of fuel) (T_2, in Fig. 1), ii) at the central region of the combustion chamber (T_3, in Fig. 1), and at several locations along the axial line of the chimney height, such as iii) at the exit of the combustion chamber and entering of the chimney (T_4, in Fig. 1), iv) at 1.1 m height (T_5, in Fig. 1), and v) at 2.8 m height (i.e., near the exit of the chimney) (T_6, in Fig. 1).

The flue gas composition was monitored continuously at 2.8 m above the exit of the stove combustion chamber (at the exit of the chimney), specifically for total volatile hydrocarbons (THC), O_2, and CO. Total hydrocarbons and CO were measured using automatic analyzers with flame ionization (Dyna-FID Hydrocarbon Gas Analyzer, model SE-310) and non-dispersive infrared (Environnement, MIR 9000) detectors, respectively. Measurement of oxygen concentration was carried out with a paramagnetic analyzer (ADC model O_2-700 with a Servomex Module). Each gas analyzer was calibrated with appropriate gas on zero and span points.

A heated probe, located at a height of 2.8 m in the chimney, and sampling line (at 190 °C) were used for THC (expressed as CH_4) sampling; the heated sampling line delivers the flue gas sample directly to the FID analyzer. The sampling probe tip was located at the axial line of the chimney, and in order to filter flue gas particles, a plug (Cerablanket) was put at the tip of the probe.

For O_2 and CO monitoring, the gas sampling and characterization systems included a water-cooled sampling probe, a set of gas conditioning and distribution units, and a set of on-line gas analyzers. The combustion flue gas was sampled at a flow rate of 2 L min^{-1} (atmospheric pressure and temperature) in a location at the exit of the chimney; the probe tip was located at the axial line of the chimney. The sampling probe was equipped with an external circulating quenching water sleeve, an ice-cooled particle gas filter, a K-type thermocouple and a Cerablanket plug at the tip for exhaust gas particle filtering. The gas conditioning and distribution units include gas flow meters, a filtering system for particulate removal, a gas sampling pump, a heat exchanger immersed in an ice bath for gas quenching and water vapor removal, and a gas distribution unit. The gas distribution unit consisted of

Table 1
Chemical characteristics of the biomass fuel.

		Pine	Eucalyptus
Proximate analysis (wt.% , as received)	Moisture	9.7	10.0
Ultimate analysis (wt.%, dry basis)	Ash	0.46	0.25
	C	51.4	48.6
	H	6.20	6.20
	N	0.16	0.16
	S	nd	nd
	O (by difference)	41.78	44.79

nd — not determined, below detection level of the equipment 0.1 wt.%.