Fuel Processing Technology 131 (2015) 182–192

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Emission of carbon monoxide, total hydrocarbons and particulate matter during wood combustion in a stove operating under distinct conditions

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ARTICLE INFO

Article history:
Received 18 July 2014
Received in revised form 28 October 2014
Accepted 13 November 2014
Available online 2 December 2014

Keywords:
Woodstove
Operating conditions
CO
PM_{10}
Particle size distribution
Emission factors

ABSTRACT

Wood combustion experiments were carried out to determine the effect of ignition technique, biomass load and cleavage, as well as secondary air supply, on carbon monoxide (CO), total hydrocarbon (THC), particulate matter (PM_{10}) and particle number emissions from a woodstove. Wood from two typical tree species in the Iberian Peninsula was selected: pine (*Pinus pinaster*) and beech (*Fagus sylvatica*). The highest CO and total hydrocarbon emission factors (EFs) were observed, respectively, for pine and beech, for high and low fuel loads. The highest PM_{10} EF was recorded for the operation with low loads for both woods. Secondary air supply produced the lowest PM_{10} emission factors. The top ignition can decrease the PM_{10} EF to less than half when compared with the common technique of lighting from the bottom. The lowest particle number emission factors were observed when operating with high loads of split beech logs and when using secondary air supply during the combustion of pine. Regarding particle number distributions, the highest geometric mean diameter (Dg), for both woods, were observed when operating with high loads (with split and non-split wood).

1. Introduction

Currently, most developed countries are heavily dependent on fossil fuels. In this context, policies that encourage the use of biomass as a renewable energy source are promoted [1,2]. Despite the recognised advantages of the use of biomass, residential wood combustion for heat production has been assessed to be a major source of fine particle mass emissions [3,4] especially during wintertime [5,6]. The problems associated with this sector occur particularly during winter, not only for being the period in which residential wood combustion is most commonly used, but also due to weather conditions of stagnation. Thus, residential wood combustion can result in local particulate matter levels comparable to those registered in high traffic areas [7]. Emissions from residential wood combustion are generated only a few metres above the ground; consequently, these emissions have not enough time to dilute, chemically oxidise and react before the population is exposed to them [8].

In Portugal, it is estimated that 2 Mton of wood is annually used in residential combustion, which contributes to particulate emissions representing around 30% of the total PM_{10} emitted by the diverse sectors of activity in the country [4].

Airborne particles arising from residential combustion have harmful effects on public health [9–11]. Some studies have been conducted to evaluate the toxicity and mutagenicity of particulate matter resulting from domestic biomass combustion [12–14]. Epidemiologic studies have linked fine particulate air pollution with negative health effects like respiratory and heart diseases or even premature dead [15,16]. Several studies have shown that the submicrometer sized particles (<1 μm) are predominant in PM emissions from this source [17]. The smaller the size of the particle the greater can be the risk for human health. Huang et al. [18] have been following cardiovascular disease patients during two years and observed a reduction in heart rate variability index due to reduced exposure to $PM_{2.5}$ and black carbon.

Taking into account the impact of these emissions and the need for compliance with legal norms, a rigorous quantification and characterisation of emissions from this sector are necessary. Additionally, and since previous works have suggested that wood and the type of combustion appliance exert a major influence on emissions from this sector [19–24], it is necessary to obtain values for Southern Europe in order to use more representative and specific locally acquired data on emission inventories and source apportionment, photochemistry and climate change models.

The technology used in domestic biomass combustion has a preponderant influence on the observed emission profiles. This is especially evident when emissions from manually and automatically operated systems are compared. Schmidl et al. [24] reported high variability between manual and automatic systems. PM_{10} concentrations obtained by these authors were between 12 and 21 mg m^{-3} for automatic systems (pellet boilers and pellet stoves) and in the range 111–151 mg m^{-3} for manually operated systems (typical stove and stove with secondary air intake). Johansson et al. [25] reported emissions 50 times higher in stoves and

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http://dx.doi.org/10.1016/j.fuproc.2014.11.021
0378-3820/

fireplaces compared to more controlled equipment. Johansson et al. [23] observed concentrations of PM in old boilers about 180 times higher than those emitted by modern pellet burners. Schmidl et al. [24] also found variability in the composition of the emitted particles. For manually operated equipment the authors showed that 70% of the PM_{10} mass consisted of total carbon (TC). For the automatic combustion equipment, the emitted particles consisted mostly of potassium inorganic salts. Fine et al. [26] reported that 40 to 100% of the fine particle mass was organic material when a conventional fireplace was used.

Although the emissions from residential wood combustion have been reported in previous studies, there is still a limited understanding of the influence of operating practices on these emissions. They vary considerably among studies, affecting the amount and composition of the flue gas emissions. In addition to batch operation mode and log size, as well as fuel quality and air supply strategies, it is also necessary to take into account that, when studying the effect of practices on emissions, each appliance has its optimal best operating conditions. Different operating practices are also relevant with respect to the effects on human health. Leskinen et al. [27] studied the toxicological responses of the fine particles resulting from three different combustion conditions, namely efficient combustion, intermediate combustion, which simulated improper air staging and partial load, and smouldering combustion. The different combustion efficiencies were simulated in a wood chip grate combustion furnace. In efficient combustion conditions, the emitted fine particles had the highest potential to cause cell death.

The objectives of the work presented here were to identify the influence of operation and real-life conditions on emissions from residential wood combustion. The investigated parameters were: (i) ignition technique (upside-down and bottom-up lighting), (ii) hot start versus cold start, (iii) fuel load and, in the case of high load, degree of cleavage of the logs, and (iv) secondary combustion air supply. This evaluation allows assessing which practices offer the greatest emission reductions and, in consequence, could constitute an important step towards an important reduction of these emissions in South Europe. Moreover, it constitutes an opportunity to characterise more thoroughly the emissions from residential wood combustion by replicating operating conditions commonly carried out in southern European countries and to point out measures that can reduce the emissions from this sector.

2. Methods

2.1. Combustion facility

The combustion tests were performed with a typical Portuguese stove (power output 9.6–18.2 kW), commonly used for domestic heating, manufactured by Solzaima (Sahara model). The rated output of the stove is 14.0 kW. This equipment is made of stainless steel with a cast iron grate (Fig. 1). The combustion chamber has a volume of 0.093 m^3, corresponding to a height of 0.44 m, a width of 0.59 m and a length of 0.36 m. It is a batch operated furnace with manual control of combustion air; besides performing heating by radiation and natural convection, it has also been designed to include air heating by forced convection.

The combustion air enters the combustion chamber through a regulating device located at the bottom of the equipment, in the ash collection hopper, below the grate of the stove. The flow rate of primary air entering in the combustion chamber was monitored by a mass flow meter (Kurz Model: 500-40 0.0 P-2). This model was designed with built-in inlet piping with the same cross section of the stove's air intake to ensure underneath air flow identical to that originally fed in under the grate. The driving force for the air flow rate throughout the combustion chamber is the natural convection resulting from the up-flowing stream of combustion hot flue gases throughout the chimney. The natural draught mainly depends on flue gas temperature, mass flow and ambient temperature. This fact may cause some variability on the results. It should be noted that the woodstove was operated under similar conditions to those practiced by household users. Contrarily to what happens in Portugal, some other countries adopted regulations, which indicate that the chimney must be able to provide a draught of at least 1.2 mm water gauge (12 Pa). The stove is equipped with a vertical chimney with an internal diameter of 0.2 m and 4.0 m tall, insulated with ceramic fibber (Cerablanket, 128 kg m^{-3}, 0.025 m, 0.23 W m^1 K^{-1}) in the first 1 m above the exit of the combustion chamber in order to guarantee operational safety.

The stove was loaded manually by putting each wood batch over the fixed grate installed in the combustion chamber. The grate was placed over a weight sensor (DSEUROPE Model 535QD-A5), which allowed continuous monitoring of the fuel mass during the combustion runs.

The combustion flue gas temperature was monitored using K-type thermocouples at several locations along the system (combustion chamber and chimney). A more detailed description of the combustion facility and appliance can be found elsewhere [28].

2.2. Combustion procedures and conditions

The combustion experiments were planned in order to evaluate the influence of the following operating variables: ignition technique (upside-down and bottom-up lighting), fuel load, in the case of high load, split (S) and non-split (NS) logs, and secondary combustion air supply. To investigate the influence of fuel load on flue gas emissions three different conditions were tested: low, medium and high load, according to the fuel weight (Table 1). These experiments were initiated by putting a batch of fuel over the bed of hot char from a previous combustion experiment, when the temperature in the combustion chamber was around 100 °C (±20 °C). All the tests to evaluate the effect of load and log cleavage (S and NS logs) on emissions correspond to a condition of "hot start". The wood was cut into logs of 30–40 cm in length, whether for split or non-split logs. Taking into account that the log size influences the combustion quality, the wood was purchased from a local supplier with a large market share in an attempt of replicating the Portuguese householder's practices. The duration of each combustion cycle depended on the operating condition, load and wood type, ranging from 30 to 95 min. The fuel ignition techniques included the conventional ignition from the bottom and ignition from the top. To initiate the combustion experiments using the bottom-up method of lighting, two pine-cones were kindled with a lighter and the fuel load was put on the very top. The upside-down fire-starting method was achieved using small pieces cut from the same wood being burned and pine-cones cracked on the top of the batch of logs. These experiments were made with wood batches of 2 kg for both fuels (medium load). The total number of batches for testing each ignition technique was between three and five (Table 1).

To investigate the influence of secondary combustion air supply, experiments were performed using a secondary air inlet (3.8 cm internal diameter) at the axial axis of the rear wall of the combustion chamber and located at 16 cm above the grate of the furnace, in order to promote a secondary combustion zone. The position and dimension of the secondary air supply was defined after discussion with the manufacturer. Secondary combustion air entered the combustion chamber by natural convection as a result of the chimney drag force induced by the up-flowing hot combustion flue gases. The aim was to enhance the mixing between pyrolysis gases from the thermal decomposition of the wood and combustion air, in order to achieve improved burnout.

2.3. Wood fuel characteristics

Biofuels were selected from tree species typical of the Iberian Peninsula and commonly used in households for domestic heating: *Pinus pinaster* (softwood) and *Fagus sylvatica* (hardwood). The moisture and ash content, together with the elemental composition, are shown in Table 2. The determination of ash and moisture contents was performed in accordance with CEN/TS 14775 and CEN 14774-3, respectively.