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Effect of fuel quality classes on the emissions of a residential wood pellet stove

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A B S T R A C T

In order to evaluate the influence of pellet quality classes, as defined by the ISO 17225-2, particulate matter and gaseous pollutants were characterized for different class fueled pellets in the emissions of a stove at partial and nominal load. Total suspended particulate (TSP) was sampled with a dilution system, then characterized for total carbon (TC), inorganic carbon (IC), water soluble organic carbon (WSOC) polycyclic aromatic hydrocarbons (PAHs) and the main soluble ions. Gas monitoring shows that CO and NO emission factors are higher for lower quality pellet. Low quality pellet emission factors are also higher for TSP and soluble ions, thus the pollutants linked to pellet ash content. On the other hand, carbonaceous component emission factors are higher for higher quality pellet; nevertheless, at nominal load, lower quality pellet emits more toxic PAHs. The higher stove power restricts instead the emissions of incomplete combustion products: CO, TSP and carbonaceous components. Principal Component Analysis (PCA) allows to have a complete overview of the obtained results: the effect of operating phase on emission factors is less strong then pellet quality, even if the pollutants produced by low heat power are more hazardous than the ones connected with pellet quality. In conclusion, the study provides not only quantitative information on the influence of pellet quality classes on stove emissions, but also their chemical fingerprint. Moreover, it indicates that the amount of hazardous emissions is also linked to stove power.

1. Introduction

In order to reach energy sustainability, systems fueled with renewable sources are more and more spread. Among these, wood pellets are today an established and valuable renewable energy source, while they were barely known in most parts of Europe only 20 years ago. From 2005 to 2010 pellet consumption almost tripled to 10 million tons and projections for 2020 foresee an increase to 25 or even up to 100 Mt in Europe. Sweden, Germany and Denmark are the countries where pellet consumption was the highest in last years. Nevertheless, if only pellet demand for heating systems is considered, Italy is the country with the highest request; in 2012, the consumption of pellet reached over 2,000,000 tons [1–4]. Pellet diffusion is in part due to Italian regulatory incentives [5], which promote systems fueled with renewable energy sources with high energy efficiency and low pollutant emissions, in part to technical-practical aspects: easy installation, easy finding fuel, automatized management.

The big and quick growth of pellet market and the high technological standard reached by domestic stoves and boilers, caused the necessity to have high quality pellet and to obtain a precise classification, thus to establish qualitative standard on raw material. Pellet characteristic standardization is necessary to optimize combustion efficiency and to avoid technical problems in system usage. To this aim, technical standards were introduced. ISO 17225-2 [6] classifies wood pellet for commercial and residential applications in three quality categories: A1, A2 and B, according to pellet properties (chemical, physical and mechanical). Some of the established parameters depend on raw materials, others to manufacturing process [7,8]. The three pellet

Abbreviations: ISO-A, A1 class quality; ISO-B, B class quality; ISO-OS, out of standard class quality; M, moisture content; A, ash content; DU, mechanical durability; Q, net calorific value; BD, bulk density; DT, dilution tunnel; NL, nominal load; PL, partial load; Flu, fluoranthene; Pyr, pyrene; B(a)A, benz[a]anthracene; Cri, chrysene; B(b)F, benzo[b]fluoranthene; B(k)F, benzo[k]fluoranthene; B(a)P, benzo[a]pyrene; D(a,h)A, dibenz[a,h]anthracene; B(g,h,i)P, benzo[ghi]perylene; I(1,2,3)P, indeno[1,2,3-cd]pyrene

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quality classes differ for ash content, mechanical durability, nitrogen, sulfur and chlorine content. Based on technical standard, a quality certification system (ENplus) was introduced in Europe [9]. Despite the efforts undertaken to produce high quality pellet, only about 50% of pellet bags sold in Italy fulfills A1 limits, while about 5% is out of standard. Moreover, in the market it is possible to find wood pellet without references to properties and characteristics [7].

It is nowadays ascertained that biomass-based residential heating systems are an important source of carbon monoxide, particulate matter (PM), volatile organic compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs), dioxins and furans [10–12]. Conversely to medium or big size plants, they have uncontrolled emissions and without abatement systems. Among biomass residential heating systems, newest generation pellet stoves and boilers guarantee the best performance; this is mainly due to combustion efficiency higher than 90% and to automatic fuel feeding, which reduces ignition and partial load operating times [11,13]. Nevertheless, also newest and most efficient pellet systems show much higher emissions compared to boilers burning natural gas, both for PM, VOCs, PAHs and CO [14].

As far as pellet stove is concerned, it was thus ascertained that they entails several advantages, because they are "CO_2 neutral" and fueled with a renewable resource, and that despite emissions of high efficiency pellet stoves are lower than other biomass heating systems [15–17], they are higher than some non-renewable energy sources. Therefore, it is necessary to deeply understand parameters that influence pellet stove emissions. In last years, research studies for pellet stoves have been focused mainly on this topic, regarding both stove operating conditions [18–21] and pellet characteristic, specifically pellet length [22], moisture content [23] type of wood [24], pellet quality [25] or pellet made by unconventional feedstock [26–29].

As far as pellet quality is concerned, several studies [13,25,30–32] demonstrate that lower quality pellet, i.e. higher ash, nitrogen, sulfur and chlorine content and lower mechanical durability, leads to higher emissions. Nevertheless, most of the studies concerns pellet boiler, while only few [13,24,25,28,33] evaluate pellet stoves. Among these, Arranz et al. [24] and Ozgen et al. [25] are the only ones, which take into account quality classes of technical standard. The first consider only gaseous emissions, while the latter entail a more comprehensive emission study, by testing certified (A1) and low-quality pellet. By the analysis of low-quality pellet characteristics, it can be inferred that it belongs to A2 class. Nevertheless, its ash content is borderline with A1, and thus even if it is defined low-quality, actually its quality is quite high. A more comprehensive study, where pellet stove emissions when they are fueled with different quality classes, as defined by ISO 17225-2, are compared, seems necessary.

The aim of this work is to evaluate how the variation in fuel properties for different pellet quality classes, as defined by ISO 17225-2, influences emissions of gases and particles in a residential pellet stove. For this reason, a commercial certified DinPlus pellet was purchased, while two different qualities of pellet were prepared ad hoc for this study, in order to have pellets fulfilling B and out of specification classes. The total particulate and its chemical composition were compared among the different fueled pellets at partial and nominal load. The chemical characterization encompasses total carbon (TC), inorganic carbon (IC), inorganic ions, PAHs and water soluble organic carbon (WSOC). According to authors' knowledge, nobody has ever determined WSOC in the emissions of pellet stoves. It seems worthwhile to undertake such a study, since pellet stoves can be both a primary and a secondary source of this pollutant. Particulate, together with gaseous emissions, was also constantly on-line monitored, to obtain information on the emission trend for the whole operating cycle. In order to take into account also of PM condensable fraction and thus to better simulate the real environmental impact of domestic pellet stoves, particulate emissions were sampled using a dilution tunnel [20,34].

2. Material and methods

2.1. Fuel production and characterization

Three different pellet quality levels were evaluated among those defined by ISO 17225-2: highest class quality (ISO-A); lowest class quality (ISO-B); out of standard class quality (ISO-OS), which is a pellet that does not fulfill the standard requirements for any of the ISO 17225-2 quality classes.

In order to have biofuels with well-defined quality level, pellets were made starting directly from raw biomass for pellet ISO-B and ISO-OS. For ISO-A, a commercial pure softwood certified DinPlus pellet (A1) was purchased from the market.

Wood sawdust (high quality) and woodchip (low quality) were used as raw materials for pellet production. They are both conifer mix, but wood species are not known. Blends were obtained on the basis of the ash contents of the two raw materials and the final ash content of the desired pellet, according to the limits of ISO 17225-2 standard. Ash content is a fundamental parameter in the definition of pellet quality classes and it is also correlated to the main quality parameters reported in standard, as found in a previous work [7]. Before the pelletisation step, a suitable quantity of water was added to blends, in order to reach the optimal moisture content needed for the pelletisation process, i.e. around 16% $w\,w^{-1}$.

Pellets were produced by a low power pellet mill driven by a diesel engine (mod. MKL229, Laizhou Chengda Machinery Co.). In this small device, ground wood is poured in a hopper placed above the pelletization chamber, where two rotating rollers compress the wood into the die holes, producing pellet by extrusion. Before the bagging, the produced pellets were first spread on a plastic cloth for cooling, then vibrosieved to remove fines.

The standard compliance of all employed pellets was checked before starting the tests by standard analyses. The physical and chemical parameters determined for each of selected pellets and their abbreviations are shown in Table 1, together with the relative standard

Table 1
Physical-chemical characterization of wood pellet and standard methods references.

Parameter	Unit	Normative references	Instruments
Moisture content (M)	$\%_{ar}$	ISO 18134-1:2015	forced ventilation oven (mod. M120-VF, MPM Instruments)
Ash content (A)	$\%_{dm}$	ISO 18122:2015	muffle furnace (mod. ZA, Prederi Vittorio & figli)
Mechanical durability (DU)	$\%_{ar}$	ISO 17831-1:2015	mechanical durability tester (Andritz Sprout rotation pellet testing apparatus)
Net calorific value (Q)	MJ kg_{ar}^{-1}	UNI EN 14918:2010	isoperibolic calorimeter (mod. C2000 basic, IKA) + elemental analyzer (mod. 2400 CHN, Perkinelmer)
Bulk density (BD)	kg m_{ar}^{-3}	ISO 17828:2015	5 L container
Nitrogen (N_{fuel})	$\%_{dm}$	ISO 16948:2015	elemental analyzer (mod. 2400 CHN, Perkinelmer)
Sulfur (S_{fuel})	$\%_{dm}$	ISO 16994:2015	isoperibolic calorimeter (mod. C2000 basic, IKA) + liquid ion chromatographer (mod. 761 COMPACT IC, Metrohm)
Chlorine (Cl_{fuel})	$\%_{dm}$	ISO 16994:2015	isoperibolic calorimeter (mod. C2000 basic, IKA) + liquid ion chromatographer (mod. 761 COMPACT IC, Metrohm)

ar: as received; dm: dry matter.