Energy 88 (2015) 650–657

Contents lists available at ScienceDirect

Energy

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

Evaluation of non-steady state condition contribution to the total emissions of residential wood pellet stove

Elisa Venturini [a, 1], Ivano Vassura [a, b, *], Cristian Zanetti [b], Andrea Pizzi [c], Giuseppe Toscano [c], Fabrizio Passarini [a, b]

[a] *University of Bologna, Interdepartmental Center for Industrial Research “Energy and Environment”, Via Angherà 22, I-47900 Rimini, Italy*
[b] *University of Bologna, Department of Industrial Chemistry “Toso Montanari”, Viale Risorgimento 4, I-40146 Bologna, Italy*
[c] *Polytechnic University of Marche, Department of Agricultural, Food and Enviromental Science (D3A), Via Brecce Bianche 10, I-60131 Ancona, Italy*

ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
15 May 2015
Accepted 25 May 2015
Available online 2 July 2015

Keywords:
Heating system
Biomass combustion
Heavy metal
Particulate matter (PM)
PAH
Soluble ions

ABSTRACT

In order to evaluate non-steady phase contribution to the total emissions of a pellet stove in real domestic operations, particulate matter and gaseous emissions were determined separately for different operating conditions, i.e. ignition, partial load, increase in power and nominal load. TSP (Total suspended particulate) was sampled with a dilution system and characterized for TC (total carbon), PAHs (polycyclic aromatic hydrocarbons), the main soluble ions, Ni, As, Cd and Pb. Gas monitoring shows that CO and NO emission factors in ignition phase markedly differ from other operating conditions: NO emission factor is lower, while CO one is much higher, since it is a product of incomplete combustion. Start-up phase emission factors are also higher for TSP, Cd and other products of incomplete combustion, i.e. TC and PAHs. Despite being a non-steady phase, the increase in power phase emission factors appreciably differ from steady state ones only for PAHs. Moreover, the PAHs emitted in non-steady state phases have a higher toxicological burden. In conclusion, in order to evaluate the real impact of pellet stove on the environment, transient conditions should be taken into account. The ignition phase, even though it lasts only 20 min, can significantly contribute to pollutant emission.

1. Introduction

Wood pellet has become an important worldwide fuel. Pellet devices as heating system were introduced about 20 years ago. In last years, their use in Europe-28 has strongly increased. Furthermore, reliable estimates indicate that their use will also increase in next years. According to the estimates, Italy will be one of the greater users of these systems in 2020, together with Germany and Belgium [16].

In Italy, the demand for wood pellet has increased steadily since 1999, led by the growth of the pellet stoves sector. In 2012, the consumption of pellet reached over 2,000,000 tons, thus confirming Italy as Europe's biggest market for pellet domestic use. In Italy, the large majority of pellets are used for space heating in the residential sector; it is estimated that about 90% is consumed in stoves and the remaining 10% is used in boilers [1,18].

The use of woody biomass as fuel in combustion plants to produce heat or electricity is also promoted in Europe by Directive 2009/28/EC [13], which aims to reduce nonrenewable resource consumption. Furthermore, the use of biomass is regarded “CO_2 neutral”, and this is a fundamental characteristic in order to reduce of 20% greenhouse gas emission within 2020, as established by 2009/29/CE Directive [14]. Nevertheless, despite the general opinion, the use of wood pellets in stove sector is not carbon neutral. As a matter of facts, the production and mainly the transport of wood pellets (frequently imported from other countries)

Abbreviations: IG, Ignition; PL, Partial load; IP, Increase in power; NL, Nominal load; DT, Dilution tunnel; DRs, Dilution ratios; 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; QV, Dry volumetric gas flow; Qm_{fuel}, Mass flow feeding fuel; NHV, Net heating value.

* Corresponding author. University of Bologna, Department of Industrial Chemistry “Toso Montanari”, Viale Risorgimento 4, I-40146 Bologna, Italy. Tel./fax: +39 051 2093863.

E-mail addresses: elisa.venturini6@unibo.it (E. Venturini), ivano.vassura@unibo.it (I. Vassura), cristian.zanetti@studio.unibo.it (C. Zanetti), a.pizzi@univpm.it (A. Pizzi), g.toscano@univpm.it (G. Toscano), fabrizio.passarini@unibo.it (F. Passarini).

[1] Present address: University of Bologna, Department of Industrial Chemistry “Toso Montanari”, Viale Risorgimento 4, I-40146 Bologna, Italy.

http://dx.doi.org/10.1016/j.energy.2015.05.105
0360-5442/

involves a significant emission of CO_2. This is important especially for Italy, where the 72% of the consumed pellet is imported [1]. Besides the advantages, which promote their incentives, there is some concern over their usage in residential heating due to the emissions of various pollutants, such as PAHs (polycyclic aromatic hydrocarbons), NO, CO, SO_x, and PM (particulate matter) [10]. For these reasons, some Italian regions (e.g. Lombardy and Marche) have banned biomass-based heating systems not complying with technical specifications or not fulfill quality standards for emissions and pellet, to prevent pollution and preserve air quality [21,22].

Domestic heating is nowadays one of the main sources of $PM_{2.5}$. According to Italian national emission inventory by Ref. [20], in 2012 in Italy, 37% $PM_{2.5}$ was due to domestic heating. Ref. [2] reported that domestic heating contribution to total $PM_{2.5}$ reached 50% in some regions such as Lombardy in 2010. According to these inventories, almost all of domestic heating $PM_{2.5}$ (98.8%) is due to biomass appliances [2,20].

These data underline how strong the impact of residential biomass heating systems is. However, pellet stove contribution to $PM_{2.5}$ emission from biomass residential appliances is low [2]. In fact, $PM_{2.5}$ emission factor for pellet stoves is lower than for other biomass residential appliances [15,17]. Pellet stove emission factors are obtained from measurements during steady state conditions, defined as the stage in the flue gas when temperature does not change more than ±5 K, in accordance to EN technical standard [8]. This approach is not realistic, because, start-up, shut-down and changes in power, i.e. all non-steady conditions, are very recurring in an operation day in domestic use. In the literature, studies focusing on the emission characterization of small scale pellet stoves during non-steady conditions are few [28,29,32,33], only two of them [28,29] undertake PM characterization. All these studies agree in an higher emission of incomplete combustion products in non-steady state conditions. However, some aspects are not properly deepened. First of all, quantitative estimates are necessary, to determine the contribution of non-steady state conditions to total daily emissions. Moreover, chemical characterization of particulate matter should be deepened. In addition to this, according to authors' knowledge, nobody has never considered another non-steady operation, the increases in power. This condition happens very often in realistic operation, because pellet stoves are usually employed in small environment and thus power changes are more recurring than for appliances which are employed in greater environments.

The aim of this study is to evaluate if non-steady phase contribution to the total emissions of a pellet stove in real domestic operations is significant compared to steady state one, taking into account also changes in the thermal power of the device. For this reason, different operating conditions, i.e. ignition, partial load (around 50%), increase in power and nominal load phases, were evaluated separately. The total particulate and its chemical composition were compared among the different operating phases while gaseous emissions were constantly on-line monitored. In order to better simulate the real environmental impact of domestic pellet stoves, particulate emissions were sampled using a dilution tunnel [29,34].

2. Material and methods

2.1. Experimental procedures

Combustion tests were carried out with a typical top-feed pellet stove (mod. 6000AV, Caminetti Montegrappa), the same device used in previous works [25,29]. In this thermal device, the heat is generated by combustion of wood pellet in a burner, which is a cast iron cup with holes on the bottom for the passage of the combustion air that is driven by an electric fan. A small auger screw supplies the pellet from the fuel storage to the burner to continuously feed the flame. A heat exchanger, placed along the hot flue gases path, transfers the heat to a secondary air flow, which is responsible for the heating of the room where the device is installed.

The emissions produced by different operating conditions occurring during a realistic domestic utilization of the pellet stove were measured. These data are fundamental in order to calculate total emissions for a specific operating cycle, knowing operating time and stove setting. The following four phases were evaluated separately: ignition (IG), partial load (around 50% of the nominal power) (PL), increase in power from partial to nominal load (IP) and nominal load (NL). The total test, including the four phases, was repeated twice. All tests were performed by firing the stove with a commercial softwood pellet.

The experimental set up for sampling and measurement of the emissions was the same used in a previous work [29]. A gas analyzer (mod. Vario Plus, MRU) was placed in the stove chimney to measure continuously temperature (Tgas), draught and composition (CO, CO_2, NO and hydrocarbons) of the flue gases. The analyzer filters and cools down a portion of flue gases, to remove dust and moisture respectively, before sending the gas to electrochemical (CO, NO) and infrared (CO_2, hydrocarbons) cells. To take into account background concentration of the gases, the analyzer performed a zero reading, by sampling ambient air, before each analysis.

In order to simulate ambient dilution conditions of the flue gases and obtain a more realistic measure of emission factors, particle matter (PM) was sampled in a DT (dilution tunnel). This approach offers different advantages, mainly: the determination of the PM condensable fraction; the possibility of making isokinetic sampling in non-steady combustions, i.e. the IG and the IP. All the flue gases exiting from the stove chimney were collected in a cowl with ambient air and cooled by means of dilution. The mean DRs (dilution ratios) were set changing the speed of the extraction fan and were maintained within the range 10÷15. A by-pass valve on DT was regulated for each test, in order to reduce the influence of DT suction on pellet stove chimney draught. Further details are described in Ref. [29].

2.2. PM sampling

TSP (Total particulate emissions) for the four real domestic operation phases previously mentioned were evaluated. Several studies [3,6] have shown that particle emissions from a pellet stove are dominated by fine particles. Therefore, TSP sampling results should not differ markedly from smaller fraction sampling ones. For each operating phase, double PM sampling was performed simultaneously by means of two samplers (mod. Isostack Basic, TECORA and mod. Aircube, Analitica Strumenti) placed in DT, each of them connected with a titanium probe equipped with a quartz microfiber filter without binder (47 mm, MK-360, MUNKTELL). In order to fulfill the isokinetic conditions for every PM sampling, the velocity of the diluted gases in DT was measured by a Pitot tube with a thermocouple and the sampling flows regulated accordingly. The temperature at the sampling points was always maintained below 40 °C.

As in a previous work [29], the IG was associated to the first 20 min after the start of the combustion process, and it was identified with the increase of CO. This phase includes the high CO and dust emission peaks produced by the initial not efficient combustion [24,29,31–33]. For the IP, the sampling of PM started immediately after nominal load was set in the stove operating at partial load and stopped when steady values of Tgas and CO, typical of