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Performance of a pellet boiler fired with agricultural fuels

Lara Carvalho [a,b,*], Elisabeth Wopienka [a], Christian Pointner [a], Joakim Lundgren [b], Vijay Kumar Verma [a], Walter Haslinger [a], Christoph Schmidl [a]

[a] Bioenergy 2020+ GmbH, Gewerbepark Haag 3, 3250 Wieselburg-Land, Austria
[b] Division of Energy Science, Luleå University of Technology, 971 84 Luleå, Sweden

HIGHLIGHTS

- ▶ Performance evaluation of a pellet boiler operated with different agricultural fuels.
- ▶ Agricultural fuels could be burn in the tested boiler for a certain period of time.
- ▶ All the fuels (except straw and Sorghum) satisfied the European legal requirements.
- ▶ Boilers for burning agricultural fuels should have a flexible control system.

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ABSTRACT

The increasing demand for woody biomass increases the price of this limited resource, motivating the growing interest in using woody materials of lower quality as well as non-woody biomass fuels for heat production in Europe. The challenges in using non-woody biomass as fuels are related to the variability of the chemical composition and in certain fuel properties that may induce problems during combustion. The objective of this work has been to evaluate the technical and environmental performance of a 15 kW pellet boiler when operated with different pelletized biomass fuels, namely straw (*Triticum aestivum*), Miscanthus (*Miscanthus* × *giganteus*), maize (*Zea mays*), wheat bran, vineyard pruning (from *Vitis vinifera*), hay, Sorghum (*Sorghum bicolor*) and wood (from *Picea abies*) with 5% rye flour. The gaseous and dust emissions as well as the boiler efficiency were investigated and compared with the legal requirements defined in the FprEN 303-5 (final draft of the European standard 303-5). It was found that the boiler control should be improved to better adapt the combustion conditions to the different properties of the agricultural fuels. Additionally, there is a need for a frequent cleaning of the heat exchangers in boilers operated with agricultural fuels to avoid efficiency drops after short term operation. All the agricultural fuels satisfied the legal requirements defined in the FprEN 303-5, with the exception of dust emissions during combustion of straw and Sorghum. Miscanthus and vineyard pruning were the best fuels tested showing comparable emission values to wood combustion.

1. Introduction

During the last 30 years, small-scale wood combustion systems have been well developed and reached a high quality and performance level in Europe. The energy efficiency has increased, the emissions have decreased, fully automatic operation systems have been developed and the combustion technology has been optimised for woody biomass fuels [1,2]. Automatically stoked systems are normally based on staged combustion, i.e. two main combustion zones are created in order to maximise the burnout rates. The primary combustion zone is located on a grate or burner plate where drying, devolatilization and char combustion takes place. The secondary combustion zone is located above the grate in the combustion chamber where the combustible gases are oxidised [2,3]. Furthermore, each combustion zone has its own air supply; primary and secondary air are supplied in the fuel bed and in the combustion chamber [4]. In this way, automatic pellet boilers can show efficiencies higher than 90% (based on the lower heating value) with CO emissions below 50 mg Nm^{-3} at 13 vol.% O_2 [3] (which corresponds to approximately 46 mg MJ^{-1}) under steady state combustion conditions.

Presently, the market for fossil fuels is unstable and their prices are constantly rising. Furthermore, Europe has the target of reaching its share of renewable energies to 20% by 2020 [5] and biomass can play an important role. However, the increasing competition

* Corresponding author at: Division of Energy Science, Luleå University of Technology, 971 84 Luleå, Sweden. Tel.: +43 7416 52238 44; fax: +43 7416 52238 99.

E-mail address: lara.carvalho@bioenergy2020.eu (L. Carvalho).

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for woody biomass in the heating sector, sawmills and pulp and paper industries are increasing the price of wood [6]. As a result, the interest for alternative biomass fuels is growing rapidly, covering woody materials of low quality, energy crops and agricultural and forest residues [7–12]. There are several benefits from expanding the spectrum of biomass raw materials used in small-scale combustion systems [13]. Besides increasing the use of renewable energies, energy crops can provide a supplemental income for farmers and at the same time show the potential of restoring degraded lands, preventing soil erosion. The value of the agricultural and forest residues can be increased by using them as fuels and more job opportunities for power and agricultural equipment industries can be created. However, burning non-woody biomass fuels in small-scale heating systems is a challenging option [11,14,15]. Compared to wood, non-woody biomass assortments have higher ash contents and a higher content of critical inorganic elements. Ash related problems are therefore expected, which affect the dust emissions [16] and cause problems during combustion due to e.g. slagging [10,17]. Slag on the grate of small-scale pellet boilers may disturb the combustion process (e.g. higher CO emissions [11]) and lead to unwanted shutdowns of the boiler [18]. High concentrations of nitrogen (N), sulphur (S) and chlorine (Cl) in agricultural fuels increase the emissions of nitrogen oxides (NO_x), sulphur dioxide (SO_2) and hydrogen chloride (HCl), respectively [4,16]; they may also cause the formation of dioxins and furans under certain combustion conditions, e.g. intermittent combustion [19,20]. Nitrogen oxides can be formed during combustion by three mechanisms referred to as thermal, prompt and fuel-bound NO_x. The thermal and prompt NO_x formation paths become active at temperatures above 1300 °C [21] which are normally not reached in small-scale combustion systems. Consequently, nitrogen oxides are assumed to be formed mainly from fuel nitrogen during biomass combustion and therefore cannot be completely avoided [21,22]. Minimisation of NO_x emissions by optimising the combustion conditions is however possible by air or fuel staging [4,16]. The release of SO_2 and to a lesser extent SO_3, result from the oxidation of the fuel sulphur [11,16]. These emissions are usually not significant for wood combustion due to the low sulphur contents of the fuel. However, at sulphur concentrations higher than 0.2 wt.% dry basis, SO_2 emissions start to be relevant due to its important role in corrosion [16]. Both NO_x and SO_2 have significant health effects (e.g. respiratory problems) [23] and are harmful gases to the environment contributing to acid rain. Incomplete combustion can lead to emissions of carbon monoxide (CO), OGC (organic gaseous carbon), PAH (polyaromatic hydrocarbons), soot and tar. CO is generally considered an indicator of the combustion quality for the reason that it is oxidised to CO_2 in the presence of oxygen and at a rate which depends on the combustion temperature, residence time and mixing rate between the combustible gaseous species from the fuel and air [3,4,16]. Biomass combustion also leads to relatively high dust emissions. Wood burning is one of the major contributors of primary particle to the atmosphere during winter times over large parts of Europe [24–28]. Small-scale combustion systems in particular play an important role [26–28]. The dust emissions can consist of both carbonaceous particles and vaporised inorganic matter mainly alkaline metals, sulphur and chlorine. Under poor combustion operation practices such as unsatisfactory air supply occurring for instance in old residential heating appliances [29,30], the dust emissions are high and dominated by particles of incomplete combustion. Typical dust emissions from modern pellet boilers operated at 100% load can vary from 10 to 30 mg MJ^{-1}, while the emissions from old residential heating appliances are between 65 and 150 mg MJ^{-1} or even higher [29,30]. The inorganic part always remains as background constituents. Efficient combustion of wood results in mainly inorganic fine particles [30,31] typically dominated by alkaline metals, such as potassium sulphates, chlorides and carbonates [32,33]. An increase in dust emissions is therefore expected when agricultural fuels are burned due to their high content of alkaline metals. The release of alkali metals is in turn influenced by other fuel elements present in agricultural fuels, most importantly chlorine, silicon and sulfur. While chlorine content enhances the release of alkali metals due to the formation of volatile alkali metal chlorides, silicates can react with potassium preventing its vaporisation [34,35]. Furthermore, sulphur in the fuel may inhibit the effect of chlorine through a sulfation reaction, in which the alkali metal chloride is converted to less volatile alkali metal sulphate [36].

The emissions and ash related problems during combustion of agricultural residues in medium and large scale combustion plants have been thoroughly investigated, e.g. [37–39]. However, there is still insufficient information available regarding their suitability in small-scale systems and whether they can be burned in accordance to the existing threshold values. Combustion of woody biomass causes emissions of gases and particulate matter which can seriously affect human health [23,40]. The introduction of new biomass fuels that potentially may cause higher emissions into the residential heating sector should be first thoroughly evaluated based on results from combustion tests. Furthermore, it is important to investigate the capability of the existing small-scale technologies in burning non-woody biomass fuels. Combustion tests provide important information to boiler manufactures by showing the limitations of the existing boiler technology and by identifying important parameters and improvements required to adapt them for a broader spectrum of biomass fuels.

The objectives of the present study are (i) to evaluate the technical and environmental performance of a 15 kW wood pellet boiler when burning different agricultural biomass fuels and (ii) to investigate the feasibility of different agricultural fuels for residential heat production. The feasibility study was done by comparing the gaseous and particle emissions as well as the boiler efficiency with the legal requirements defined in the FprEN 303-5 (final draft of the European Standard 303-5, Heating boilers – Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW – terminology, requirements, testing and marking) [41].

2. Material and methods

2.1. Fuel properties

The combustion tests were done with pelletized fuels from wood (*Picea abies*) with 5% rye flour and seven agricultural raw materials: straw from wheat (*Triticum aestivum*), Miscanthus (*Miscanthus × giganteus*), maize (*Zea mays*), vineyard pruning (from *Vitis vinifera*), wheat bran, hay and Sorghum (*Sorghum bicolor*). Straw was harvested in the Spring of 2006. Miscanthus was harvested between January and March of 2006. Maize was harvested in the Spring of 2006 and all the plant (stem and cob with maize grains) was pelletized. Wheat bran is the hard outer layer of a wheat grain. It is normally a by-product of milling in the production of refined wheat flour. Hay is a mixture of grasses, legumes and/or other herbaceous plants. Its composition depends greatly on the region where it grows. Detailed information about the Sorghum pellets tested is given elsewhere [42]. No information regarding the place of growth and the time of harvesting is available for the pellets from vineyard pruning, wheat bran and hay.

Chemical and thermal properties of each of the experimental pellets were analysed according to the relevant standard methods and the properties are presented in Table 1. The ash and moisture contents of the pellets were analysed according to CEN/TS 14775,