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Combustion of agricultural residues: An experimental study for small-scale applications

Evelyn Cardozo [a,b,*,1], Catharina Erlich [a,2], Lucio Alejo [b,1], Torsten H. Fransson [a,3]

[a] Department of Energy Technology, School of Industrial Technology and Management (ITM), Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden
[b] Facultad de Ciencias y Tecnología (FCyT), Universidad Mayor de San Simon (UMSS), Cochabamba, Bolivia

HIGHLIGHTS

- Comparison of combustion behavior of agro-residues and wood pellets is presented.
- NO, CO and SO_2 emission levels as function of biomass sort are showed.
- Conversion efficiency of elemental fuel compounds into gaseous products is examined.
- Sugar cane bagasse pellets showed similar combustion behavior as wood pellets.
- Sunflower husk pellets and Brazil nut shells presented higher emission levels.

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ABSTRACT

Energy services could be greatly improved by using of residues from local food industries in small-scale combustion units. Wood pellets are a reliant and proven fuel to be used in small-scale combustion units. However, these units should preferably be able to use different types of biomass depending what it is locally available. Therefore, studies have been focused on exploring the suitability of using agricultural residues for small-scale heat and power generation using direct combustion. This study targets to compare the combustion of different agricultural residues in a single unit designed for wood pellets. The different biomass fuels used are Ø6 mm and Ø8 mm wood pellets, Ø6 mm bagasse pellets, Ø6 mm sunflower husk (SFH) pellets and Brazil nut (BN) shells. The results reveal a decrease in the fuel power input, higher oxygen levels in the flue gases and shorter cycles for ash removal when using the agricultural residues. The excess air ratio was calculated based on a mass balance and compared with a standard equation showing a good agreement. CO and NO emission levels as well as the relative conversion of fuel-C to CO were higher for the BN shells and SFH pellets in comparison to the other biomass types. SO_2 emission was estimated based on the analysis of unburned sulfur in ash and mass balances; the higher estimated levels corresponded to the BN shells and SFH pellets. All the biomass sorts presented over 95% relative conversion of fuel-C to CO_2. Wood pellets and BN shells presented the highest amount of unburned carbon in ash relative to the fuel-C. The relative conversion of fuel-N to NO and fuel-S to SO_2 were higher for wood pellets. Bagasse pellets showed similar emission levels and relative conversion efficiency to wood pellets.

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1. Introduction

Biomass has been used by mankind through thousands of years as a primary energy resource, but after the oil crisis of the 1970s, the interest in using this resource in modern energy conversion facilities starts to grow rapidly. Aside from being locally produced and enabling less dependence on oil, biomass is also considered to be CO_2 neutral according to today's terminology [1].

Among different types of biomass, a large amount of agricultural residues are available during the harvest time and as by-products in food industries. Using these residues for energy purposes contributes to avoiding disposal problems. Some agricultural residues from the harvest are used as fertilizers or as fodder; meanwhile, in many places parts of the residues are still burned in the field [2]. This generates high emission of unburned hydrocarbons and particulate matter causing severe health problems for the local residents. Agricultural residues generated as by-products in food industries are often used to meet only the energy demand

* Corresponding author at: Department of Energy Technology, School of Industrial Technology and Management (ITM), Royal Institute of Technology (KTH), 100 44 Stockholm, Sweden. Tel.: +46 8 790 74 77; fax: +46 8 20 41 61.

E-mail addresses: evelyn2@kth.se (E. Cardozo), erlich@kth.se (C. Erlich), lalejo@fcyt.umss.edu.bo (L. Alejo), fransson@energy.kth.se (T.H. Fransson).

[1] Tel.: +591 4 23 36 48; fax: +591 4 23 25 48.
[2] Tel.: +46 8 790 74 68; fax: +46 8 20 41 61.
[3] Tel.: +46 8 790 74 75; fax: +46 8 20 41 61.

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Nomenclature

Symbol	Parameter
BN	Brazil nuts
Ca.	Calculated
C_{fuel}	Carbon content in the fuel (% mass)
C_{ash}	Carbon content in ash (% mass)
d.a.f.	Dry ash free basis
d.b.	Dry basis
λ	Excess air ratio
$n_{\mathrm{F.G.(d.b.)}}$	Flue gas flow in dry basis (kmol/h)
LHV	Lower heating value (MJ/kg (d.b.))
$\dot{m}_{X-XY}$	Mass flow of C, N or S (X) in CO_2, CO, ash, NO or SO_2 (XY) (kg/h)
$\dot{m}_{X-fuel}$	Mass flow of C, N or S (X) content in the fuel (kg/h)
F	Mass of the test fuel fired hourly (kg/h)
M_{air}	Molecular mass of air (kg/kmol)
M_c	Molecular mass of Carbon (kg/kmol)
M_{SO_2}	Molecular mass of SO_2 (kg/kmol)
n_{N_2}	N_2 molar flow (kmol/h)
AF_{real}	Real air fuel ratio (kg air/kg fuel w.b.)
Sunflower husk	SFH
n_{SO_2}	SO_2 molar flow (kmol/h)
S_{fuel}	Sulphur content in fuel (% mass)
S_{ash}	Sulphur content in ash (% mass)
AF_{stoich}	Stoichiometric air fuel ratio
$X_{N_2\text{-}air}$	Volume fraction of N_2 in air
w.b.	Wet basis

of the production process in a separate cogeneration unit operating during the harvest season [2,3]. However, often the energy demand of the process is lower than the energy potential of the residues. Among food industries that have potential surplus of residues; cane sugar-ethanol, sunflower oil and the emerging industry of Brazil nuts (*Bertholletia excelsa*) are the targets in this study. In South-American countries, important cane sugar-ethanol and sunflower oil industries exist in both small- and large-scale. In this region, 822 million tons of sugar cane was produced and almost three million tons of sunflower seeds in 2010 [4]. Brazil nuts based industry is an emerging important local business in the Amazonian region that generates large amounts of residues during the shelling of the nuts [5]. The production of Brazil nuts with shells was estimated to be around 85,600 tons in South-America in 2010 [4]. If these three residues are used in modern small-scale combustion technologies integrated with a prime mover to generate heat and electricity, energy services could be improved in rural areas. In Latin America, the rate of rural electrification was 73% in 2009 [6].

Among small-scale combustion technologies, pellet fuel based technologies are a reliant and commercial alternative, especially in Europe [7,8]. These technologies allow an automatic operation and the use of a uniform fuel [7,8]. Upgrading agricultural residues and using them in this type of technologies can facilitate the spreading of this technology overseas. However, at the moment these small-scale combustion technologies are not enough tested for other biomass fuels than wood. It is therefore significant to compare different locally available biomass fuels in a single combustion unit in order to facilitate the development of fuel-flexible pellet combustion units. The combustion unit could be directly connected to a Stirling engine or an externally fired micro-gas turbine for power generation. This integration offers some advantages over the gasification-IC engine power generation option. Among the advantages there are less need of gas cleaning and significantly reduced risk for CO poisoning of operators. Generally, the need of manual control and guarding is significantly reduced since direct combustion units do not produce toxic nor explosive gases as in the case of gasification units.,

Bagasse pellets were used in a small-scale gasification unit by Erlich and Fransson [9]. In this study bagasse and wood pellets showed similar conversion behavior and temperature profile during gasification; meanwhile pellets from palm oil residues showed completely different behavior and lower efficiencies. The results in this study can be extrapolated to other thermal conversion technologies. Therefore, the potential of using bagasse pellets in modern thermal conversion technologies designed for wood is high, but need further studies to confirm this hypothesis. An important difference between wood and bagasse is the content of ash, which could contribute to operational differences.

A new market of sunflower husks pellets is growing in some European countries like Belgium, Ukraine and Poland [10-12]. As a result, some studies were focused on the performance of this residue as fuel in small heating appliances. Verma et al. [11,12] compared the combustion of sunflower husk pellets against other biomass pellets such as wood, apple pomace, peat and straw using a residential pellet boiler with a horizontally fed burner. In this study, sunflower husk pellets showed the highest dust released, but permissible levels of CO emission and efficiencies in comparison to the rest of pellets. Smith and Lindley [13] used sunflower husk pellets and sunflower stalk briquettes in a residential boiler with a gravity-fed system and presented overall boiler efficiencies of 62% and 67%. Other studies have examined the burning profile [14], kinetics [15] and slagging tendencies [16] of the sunflower husk (non-pelletized) under laboratory conditions. However, further studies are required to obtain a more representative evaluation of the combustion behavior of sunflower husk pellets to show the differences arising due to the use of other types of pellet burners than the ones mentioned above.

Brazil nut shells have not been tested yet in small-scale energy appliances (as found by the authors). A kinetic model based on the pyrolysis of the shells between 350 and 850 °C has however been reported showing an efficient conversion of the shells into useful products [5]. Therefore, the potential use of these shells in small combustion units needs to be investigated as well as their possible use for heat and power generation in single households or villages in the Amazonian region.

Wood pellets as a proven and commercially available fuel have been a reference for performance comparison with other biomass pellets in small combustion units [11,12,20,21]. Previous studies have presented data of flue gas compounds, emissions and efficiencies during the combustion of different agricultural residues in form of pellets [11,12,17–22]. Miranda et al. [17] compared O_2, CO and NO_x concentrations and combustion chamber temperatures as function of the time for blends of pelletized residues from olive pomace and pyrenean oak. They also calculated efficiencies as a function of the CO_2 measured. Gonzales et al. [18] analyzed the influence of the fuel mass flow, draught and fuel mixtures using tomato, forest, cardoon pellets and olive stone as a function of the flue gas concentration, thermal losses, excess air ratio and efficiency. Dias et al. [19] tested four different biomass pellets and provided information about CO and NO_x emissions as well as thermal losses and oxygen levels as a function of the input energy. These authors also measured temperatures, O_2 and CO levels during the start-up of a residential boiler. Limousy et al. [20] examined the gaseous products, particulate matter, combustion

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