Analysis of the combustion of pellets made with three Cameroonian biomass in a domestic pellet stove

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Abstract

In Sub-Saharan houses, the growing demand of fuels calls for the identification of new renewable and local resources such as biomass, suitable for energy production in small-scale stoves. In these countries, the three-stone-fire type is the most common stove and its use usually leads to high gaseous and particulate emissions. In the present study, combustion experiments of pellets made with three Cameroonian biomass in three different proportions were performed in a domestic pellet stove. The gaseous and particulate emissions were measured in derivations of the exhaust tube through appropriate gas analyzers or collecting filter. The CO concentration was measured between 476 and 675 mg/Nm^3, depending on the pellets. The Total Suspended Particles (TSP) were measured in the range 130-240 mg/Nm^3, depending on the pellets. These gaseous and TSP emissions were much higher than that obtained when burning normalized EN+ pellets in the same

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pellet stove. The combustion efficiency was evaluated between 68.5 and 80.2%, depending on the pellets, through standard computations. These values were found in the same range as that (78.2%) obtained when burning normalized EN+ pellets in the same domestic pellet stove.

1.   Introduction

In Sub-Saharan Africa, over 700 million people depend on solid biomass fuels for cooking and if necessary heating energy needs [1]. Such huge needs lead to deforestation and also to health problems, because of the gaseous and particulate emissions which occur during the biomass combustion in domestic stoves [2]. Because waste (wood chips, sawdust, hulls…) produced from forest- or agro-industries are generally available in large quantities, they should be used as biofuels for cooking purpose or heat production in domestic stoves, thus realizing a circular economy which could further reduce the deforestation process. Before the use of forest- or agro-industrial waste for cooking purpose or heat production at a domestic scale, these waste may be first assembled in pellets for easier transportation from their production zone to their final use zone and even during their use in domestic stoves. In [3], the authors compared different processes to use biomass (from crop and waste) as fuel, among which pelletization which leads to an increase of the energetic density that allows to transport more energy per volume. Starting in the 1980s in North America and in Europe, the use of wood pellets for energy production really increased at the end of the 1990s with the implementation of large-scale pellet production [4]. In Europe, the quality of commercial pellets for domestic use is regulated by the certification UNI EN ISO 17225-6:2014

[5], which especially fixes upper values of the gaseous and particulate emissions. This European regulation is compared to the Canadian and American ones in [6].

The combustion of pellets in domestic pellet stoves was analyzed in numerous papers, see the review [7] for example. Such studies were devoted either to the analysis of the subsequent gaseous or particulate emissions or to the evaluation of the performance of the domestic burner, or even both. The gaseous emissions from the combustion at 11% of oxygen of pellets made with vineyard residues and wood chips were analyzed in [8]. The CO concentrations were measured below 1000 or 500 mg/Nm^3 for vineyard residues or wood chips, respectively. The heavy metals present in the flue gas were also analyzed in this study. In [9-11], the authors analyzed the emissions from the combustion at 11% of oxygen of pellets made with grape pomace or wood residue in different proportions. The CO emissions were measured between 1000 or 8000 ppm. As Polycyclic Aromatic Hydrocarbons (PAH) are products of incomplete combustion and well-known carcinogenic and mutagenic compounds, they were measured between 8 and 296 µg/MJ during the combustion of pellets made with pine sawdust, cork residues and kiwi residues in a domestic pellet stove [12]. In [13], the particulate matter (mainly particles with sizes below 2.5 µm ($PM_{2.5}$) and above 10 µm) emitted during the combustion of pine pellets was measured between 160 and 490 mg/Nm^3 at 13% O_2. In [14], the combustion of pellets made of sawdust and wood shavings led to emissions lying between 40 and 240 mg/m^3. The emissions from the combustion of pellets made with different waste (pine, industrial wood wastes and peach stones) were analyzed in [15] at 13% O_2, together with the performance of the pellet stove. The CO emissions were measured below 600 or 1000 ppm, the NO emissions below 450 or 400 ppm, depending on the stove thermal input. The gaseous and particulate emissions from the combustion of wood pellets in a residential pellet stove were analyzed in [16] and the authors here proposed experimental conditions to reduce the CO, Total Suspended Particles (TSP) and PAH emissions. The mean value among the different

conditions of the CO emissions was computed at 127.5 or 1195.7 mg/Nm^3, depending on the stove. That of NO emissions was computed at 53.3 or 80.8 mg/Nm^3, depending on the stove. In [17], the authors analyzed the emissions during the combustion of EN+ pellets, or of pellets made with peat, reed canary grass, apple juice industrial waste, citrus pectin shell, sunflower husk, or with two kinds of wheat straw (100% pure straw or straw with 2wt% of hydrated lime [Ca(OH)$_2$] as an additive). The CO emissions were measured between 84 and 4221 mg/Nm^3, the NOx emissions between 95 and 180 mg/Nm^3 and the dust emissions between 20 and 650 mg/Nm^3, depending on the pellets. The gaseous and particulate emissions from the combustion of three different pellet quality levels, defined by ISO 17225-2:2014 [18], were evaluated in [19]. The CO concentrations were measured between 643 and 171 ppm, the NO emissions between 32 and 102 ppm and the TSP between 4 and 5 mg/m^3. In the recent paper [20], fuel indexes were proposed to predict total TSP and nitrogen oxide emissions from biomass combustion based on the elemental composition of the fuel. Thirty-nine biomass-derived fuels were tested in this study. The PM emissions were measured between 7 and 348 mg/MJ.

The performance of different domestic pellet stoves was analyzed in [21-22], with pellets made with straw (triticum aestivum), miscanthus (miscanthus giganteus), maize (zea mays), wheat bran, vineyard pruning (from vitis vinifera), hay, sorghum (sorghum bicolor) and wood (picea abies). These combustion efficiencies were measured between 62.0 and 75.8% in [21] and higher than 90% in [22].

Very few studies were devoted to the analysis of the combustion of pellets made with tropical waste. For example, the combustion of pellets made with Jatropha curcas fruit shells or seed cakes in a domestic pellet stove was analyzed in [23]. The CO emissions were measured between 1420 and 13055.6 mg/Nm^3 at 13% O$_2$. The combustion of pellets made with spent coffee ground in a small

pellet stove was analyzed in [24], with CO and NOx concentrations in the flue gas equal to 643 ppm and 163 ppm, respectively, see also the references in these two papers.

The values of the emissions and stove performances which are gathered in the preceding lines exhibit very large dispersions, due to differences concerning the experimental conditions and the pellet stoves or boilers. Consequently, their comparison with that of the present study is limited.

On another aspect, few papers analyzed the gaseous and particulate emissions present in Sub-Saharan houses when burning tropical wood residue in a domestic stove, being the three-stone-fire type the most common in the area [1, 25-26]. For example, the CO concentration was measured in homes equipped with a three-stone-fire stove at 29.5 ppm (47 mg/Nm^3) and the PM$_{2.5}$ concentration was measured at most at 5494 µg/m^3 in [1].

The present study analyzes the possibility to use three selected Cameroonian forest- and agro-industrial residue, first assembled in pellets, for combustion in a domestic stove. The selected Cameroonian forest- and agro-industrial residues were: palm nut shells, palm nut mesocarp fiber and coffee husks, because of their large availability in Cameroon [27]. Cameroon was the 16th producer of palm oil in the world in 2013 with 225,000 tons and the 31th coffee producer in the world in 2014 with approximately 41,800 tons [28]. It has about 28 million hectares of forests and it is the 6th main exporter of tropical wood in the world. However, 220 thousand hectares of forest are lost each year in this country, mainly because of population and arable and permanent cropland, trade in forest products, fetching of fuel wood and cattle stock [29].

The growing demand of fuels calls for the identification of new resources of biomass, suitable for energy production in small scale appliances. For this reason, the three base agro-industrial residues were mixed in different proportions, creating three biofuels. These biofuels were characterized before performing combustion experiments in an equipped domestic pellet stove. The combustion efficiency was computed and the gaseous and particulate emissions were measured. These

characterizations and combustion characteristics were compared with that obtained when burning normalized EN+ pellets in the same pellet stove. The present study thus fills a gap before the possibility to use pellets made with such local tropical forest- and agro-industrial residue as an interesting combustible in a domestic stove, thus realizing a circular economy.

2.   Materials and methods

2.1.   Materials

Three base Cameroonian materials will be considered in this study: palm nut shells (PNS), palm nut fibers (PNF) and coffee husks (CH). Palm nut shells are by-products of palm oil production. They are obtained after extraction of palm oil, grinding of the nut and extraction of almonds from the nuts. Palm nut fibers are by-products of palm oil production as well. They are obtained after extraction of palm oil, just separating them from the nuts. The coffee husk, also called mesocarp, is the fleshy part that covers the coffee beans. Dried coffee pulp is obtained in large quantities when the coffee fruit is husked after drying.

The three base materials were collected in the Littoral region of Cameroon. Palm nut mesocarp fibers and palm nut shells were provided by a Joint Initiative Group in Edea, Department of Sanaga Maritime, Cameroon. Coffee husks were collected from a coffee peeling factory in Nkongsamba, Moungo Department, Cameroon. The different residues were sun dried (uncontrolled temperature) for two weeks before characterization. Figure 1 gathers pictures of the three base materials considered in the present study, after this drying process.

Fig. 1. Palm nut shells a), Palm nut mesocarp fibers b), Coffee husk c).

The three base materials were separately milled with a Retsch SM100 cutting mill equipped with a 1 mm sieve.

For the combustion experiments, three kinds of pellets were produced to also analyze the impact of their composition. A Kahl 14-175 mill was used with a die having a diameter equal to 6 mm and a length set at 30 mm under a temperature of 70 °C and with a frequency of 60 Hz. The three base materials (PNS, PNF and CH, respectively) were mixed in mass proportions of 30, 60 and 10 (hereafter denoted as 30/60/10), or 60, 30 and 10 (60/30/10), or 45, 45 and 10 (45/45/10). The amount of CH was reduced to a low proportion in both pellets because combustion experiments performed on pellets only made with CH proved that this combustible produces important ash amounts during its combustion, see also Table 2.

The results of the ultimate analyses of the three base materials are indicated in Table 1. For comparison, ultimate analyses were performed on EN+ pellets. Since it was impossible to perform ultimate analyses on the three types of pellets which will be considered in the further combustion experiments, simulations of these ultimate analyses are proposed as combinations of that of the three base materials with their mass proportions in the pellets. Such simulations are validated when comparing experimental and simulated ultimate analyses for another type of pellets which was considered in [30].

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Table 1

Ultimate analyses on dry basis of the three base materials and of the EN+ pellets [31]. H/C and O/C atomic ratios computed from the values of the ultimate analyses. Simulations of the ultimate analyses for the three types of Cameroonian pellets.

Sample	Ultimate analysis (%)					H/C ratio	O/C ratio
	C	H	O	N	S		
PNS	55.7	9.1	27.4	1.3	0.2	1.96	0.37
PNF	55.7	6.3	37.7	0.3	nd[a]	1.36	0.51
CH	54.2	6.8	36.1	2.7	0.2	1.51	0.50
EN+	47.1	6.1	46.6	<0.1	<0.03	1.55	0.74
30/60/10 sim	*55.6*	*7.2*	*34.5*	*0.8*	*0.1*		
60/30/10 sim	*55.6*	*8.0*	*31.4*	*1.1*	*0.1*		
45/45/10 sim	*55.6*	*7.6*	*32.9*	*1.0*	*0.1*		

[a]: not detected

The three Cameroonian base materials contain quite similar C percentages, CH sample having the lowest and PNS and PNF the highest C content. CP has the highest O content. Very low sulfur amounts were detected or were lower than the detection limit in the four samples, which is quite usual for such materials. This is interesting for combustion and energy production, as emissions of sulfur-based pollutants emitted through combustion will be reduced to low levels. When comparing the experimental and simulated ultimate analyses of EN+ and Cameroonian pellets, EN+ pellets have less carbon and more oxygen.

The H/C ratio of PNS is high when compared to the other samples and to conventional

lignocellulosic materials, because of its high hydrogen percentage. Nevertheless, the values of H/C and O/C ratios of the four samples, whose mean values are equal to 1.44 and 0.48, are usual for lignocellulosic materials [32].

Table 2 gathers the proximate analyses and the higher and lower heating values of the Cameroonian and EN+ pellets [31]. It also gathers simulated values of the proximate analyses, higher and lower heating values for the three types of pellets which will be considered in the combustion experiments. The moisture content was determined once the sample was put in a Memmert VM400 oven at 105±2 °C for 120 hours. This long experiment duration was chosen to ensure a stabilization of the sample mass at the end of the drying process. A Nabertherm muffle furnace was used to determine the ash content at 550 °C or 815 °C, according to NF EN ISO 18122 [33]. The higher heating value (HHV) was determined placing the sample in a metal crucible (accuracy 0.1 mg) in a IKA C200 calorimeter. The lower heating value (LHV) was then deduced from the HHV, removing the energy required to take into account the condensation of water coming from both the moisture content and hydrogen proportion of the sample. Corrected lower heating values were finally computed on dry and ash-free materials through the formula:

$$LHV_{daf} = LHV \times \frac{100}{100 - Ash_{550}}, \qquad (1)$$

where Ash_{550} is the ash percentage determined at 550 °C, given in Table 2.

Table 2

Proximate analyses and higher and lower heating values on dry basis of the three base materials and of the EN+ pellets [31] (M=Moisture, FC=Fixed Carbon, VM=Volatile Matter). Simulations of the ultimate analyses and higher and lower heating values for the three types of Cameroonian

pellets.

Sample	Proximate analysis % (as received)					HHV MJ/kg	LHV$_{daf}$ MJ/kg
	M	FC	VM	Ash 550 °C	Ash 815 °C		
PNS	11.6	21.3	63.9	3.2	0.7	19.0	17.2
PNF	16.0	12.1	64.5	7.4	5.4	22.6	22.5
CH	18.2	20.7	50.6	10.5	6.8	16.0	15.7
EN+	8.0	79.3	12.7	0.3	0.3	18.8	17.7
30/60/10 sim	*14.9*	*15.7*	*62.9*	*6.5*	*4.1*	*20.9*	*20.2*
60/30/10 sim	*13.6*	*18.5*	*62.8*	*5.2*	*2.7*	*19.8*	*18.6*
45/45/10 sim	*14.2*	*17.1*	*62.8*	*5.8*	*3.4*	*20.3*	*19.4*

The proximate analyses of the three base materials present differences: PNF has the highest percentage of volatile matter. CH has the highest percentages of fixed carbon, ash and moisture and the lowest percentage of volatile matter.

The moisture and ash contents are much lower for EN+ pellets than for the Cameroonian pellets. These EN+ pellets have a much higher fixed carbon percentage and a much lower volatile percentage than the Cameroonian ones. These elements will have consequences on the combustion behavior of the pellets.

LHV values of the base materials, especially that of PNF, are in the upper range of data found in the literature for lignocellulosic materials. Biomass indeed usually exhibit LHV values between 13 and 18 MJ/kg [4,7]. These high values are related to the high carbon percentage of each base material, see Table 2, in comparison with that of conventional biomass for which the carbon percentage is usually close to 46% [31].

Atomic absorption experiments of the ash from the different samples were realized in a

spectrometer (Perkin Elmer) PinAACLe 900F, after mineralization in a microwave ETHOS 1, to determine the amounts of some minerals. Table 3 gathers these amounts for the Cameroonian and EN+ pellets [31]. It also gathers simulated values of the mineral amounts for the three types of pellets which will be considered in the combustion experiments.

Table 3

Amounts (%=g/100 g) of some minerals contained in the ash obtained at 550 or 815 °C (except for EN+ pellets) from the Cameroonian and EN+ pellets [31]. Simulations of the mineral amounts for the three types of Cameroonian pellets.

Sample	Temp (°C)	Ca	Mg	K	Na	Cu	Fe	Zn
PNS	550	9.4	4.0	10.4	0.40	0.07	2.3	0.02
	815	8.3	4.5	9.4	1.10	0.08	2.7	0.03
PNF	550	6.4	1.1	27.4	0.20	0.02	0.6	0.01
	815	8.6	2.6	21.5	1.50	0.04	2.6	0.02
CH	550	1.1	0.3	2.9	0.20	0.04	4.9	0.02
	815	1.3	0.7	2.6	1.50	0.04	4.3	0.02
EN+	550	5.8	0.8	5.3	0.06	n.d[a]	0.5	0.01
30/60/10 sim	*550*	*6.8*	*1.9*	*19.9*	*0.3*	*0.04*	*1.5*	*0.01*
	815	*7.8*	*3.0*	*16.0*	*1.4*	*0.05*	*2.8*	*0.02*
60/30/10 sim	*550*	*7.7*	*2.8*	*14.8*	*0.3*	*0.05*	*2.1*	*0.02*
	815	*7.7*	*3.6*	*12.4*	*1.3*	*0.06*	*2.8*	*0.03*
45/45/10 sim	*550*	*7.2*	*2.3*	*17.3*	*0.3*	*0.04*	*1.8*	*0.02*
	815	*7.7*	*3.3*	*14.2*	*1.3*	*0.06*	*2.8*	*0.02*

[a]: not determined

The major elements (calcium, iron, magnesium and potassium) originate from the husks. The corresponding percentages expressed in oxide speciation range from 2-13%, 0.9-7%, 0.5-8%, 4-43%, respectively for CaO, Fe_2O_3, MgO and K_2O. If these values highly vary, depending on both the nature of the soil and material, they are consistent with the results obtained by Maschowski et al. with other Cameroonian biomass [34]. This again will have consequences on the combustion behavior of the pellets. The PNF sample contains much more potassium than the other samples. The CH sample contains much more iron than the other samples. The PNS sample contains much more calcium and magnesium than the other samples. Whatever the sample, the quantities of copper and zinc are very low. The Cameroonian pellets contain much more potassium than the EN+ ones.

The fractions of extractives, hemicellulose, cellulose and lignin of the Cameroonian and EN+ pellets were determined using Van Soest's protocol [35], which consists of three stages. First, a neutral fiber detergent is used to solve the extractive part of the sample. Then an acid fiber detergent is used to solve the hemicellulose part of the sample. Finally, the cellulose part is removed using sulfuric acid at 72% in mass. Finally, only the lignin part remained. The values of these fractions are gathered in Table 4, for the Cameroonian and EN+ pellets [31], which also contains simulations of the different fractions of the three types of Cameroonian pellets.

Table 4

Values of the fractions of the four constituents (E=extractive, H=hemicellulose, C=cellulose, L=lignin) for the four samples and for the EN+ pellets [31], as determined through Van Soest's protocol. Simulations of the four constituents in the three types of Cameroonian pellets.

Sample	E	H	C	L
PNS	0.12	0.20	0.45	0.23
PNF	0.20	0.24	0.35	0.21
CH	0.05	0.07	0.60	0.28
EN+	0.10	0.19	0.44	0.27
30/60/10 sim	*0.16*	*0.21*	*0.41*	*0.22*
60/30/10 sim	*0.14*	*0.20*	*0.44*	*0.23*
45/45/10 sim	*0.15*	*0.21*	*0.42*	*0.23*

The three base materials here present large differences. PNF contains a large proportion of extractives and a low proportion of cellulose. On the contrary, CH contains low proportions of extractives and hemicellulose, but a high proportion of cellulose. The fractions of lignin are almost the same for the four samples. The Cameroonian and EN+ pellets contain quite similar proportions of the four constituents.

In complement to these characterizations, pyrolysis and combustion experiments where performed in a thermobalance on the three base materials and on crushed pellets. A kinetic modeling was also performed based on the lignocellulosic representation of these materials to estimate the kinetic parameters associated to the pyrolysis and combustion of the materials. The corresponding results are presented in the supplementary material, section S2, see also [30] for the complete thermogravimetric analyses of these materials under nitrogen and under air.

2.2. Combustion experiments

The combustion experiments were realized in a domestic pellet stove supplied by Hoben (Model H5 Signature Color Steel), whose schematic principle is presented in Fig. 2.
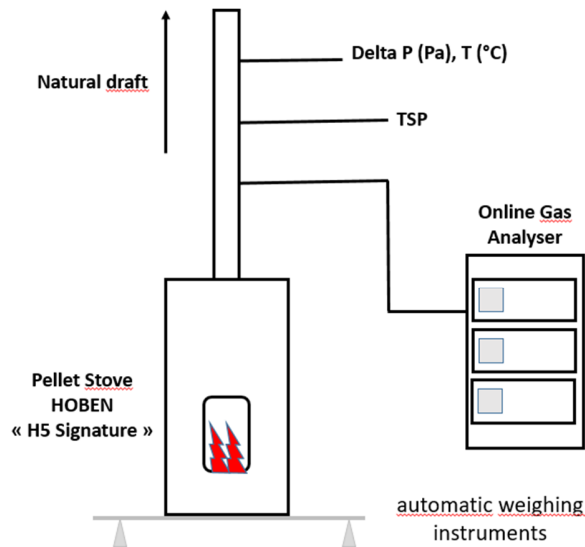
Fig. 2. Scheme of the experimental combustion setup.

The steel inner wall of the combustion chamber is covered with vermiculite plates to concentrate the heat. The presence of a fan that forces an air circulation in the pot and to the exhaust and consequently leads to a high air factor in the pellet stove. Ignition is realized using an electrical resistor located at the bottom of the combustion pot. An Intelligent Regulation System (IRS) adjusts the stove power from 1.3 to 6.3 kW. It is based on a set temperature which is fixed by the user and on the ambient temperature which is measured by a thermostat. During a combustion test, the pellet stove adjusts the combustible and air amounts to the heat requirement: here power of 100% and air modulation of 50%. To avoid possible variations of the power of the pellet stove, the combustion experiments were indeed performed at its maximal power. The air modulation value corresponds to the rotation frequency of the fan and indirectly to the oxygen rate in the fumes (a linear trend between air modulation value and oxygen rate in the fumes was indeed observed during the experiments). The air modulation value allows the adaptation of the stove to the exhaust tube and

the draught during combustion. The air modulation value was determined burning EN+ pellets to obtain burning conditions and emission values according to the manufacturer specifications.

A pellet stove usually works with an air excess higher than 12%, to get a flame in the combustion chamber. In the present study, this air excess value, set at 15% for EN+ pellets, was used for the combustion of Cameroonian pellets.

During a combustion experiment, pellets fall down in the burn pot by an auger system which consists of a screw auger starting at the refillable pellets hopper. The pellet feeding rate is automatically regulated by the stove SRI and the pellet consumption rate is measured during the combustion experiments thanks to a balance located under the stove platform. The pellet stove is not equipped with a lambda probe to monitor oxygen content.

Throughout the combustion process, the flue gas temperature is recorded, which allows to determine the input power and the useful power of the pellet stove as well as the associated heat losses. The combustion chamber and gas exhaust temperatures are continuously measured (every second) during the combustion experiments, according to DIN EN-304:2018-02 [36].

Each combustion experiment was performed during approximately two hours. The successive stages of a combustion test were: ignition from ambient temperature, warm-up and stabilization, the stabilization criterion being the temperature of the fumes (exhaust temperature), see Fig. 3.
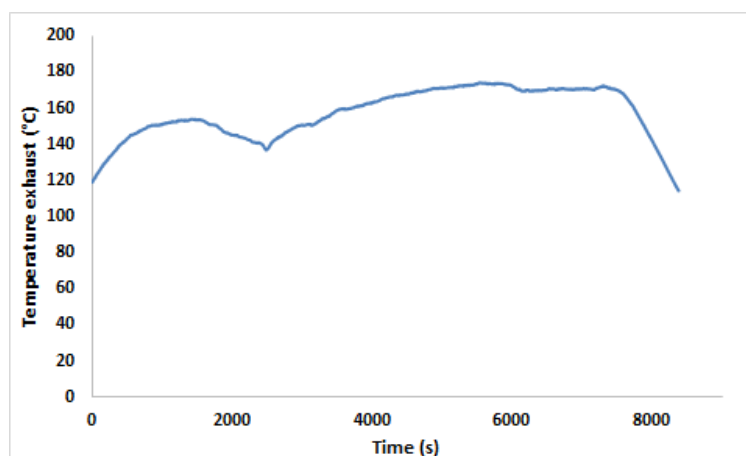
Fig. 3. Gas exhaust temperature measured during an overall combustion experiment of the 60/30/10 pellets.

The gas exhaust temperature fluctuates until approximately 6,000 s where a steady regime appears which lasts until approximately 8,000 s. Only this stage of the combustion experiment will be taken into account in the present study.

During the combustion test, ash migrate to the bottom of burner pot where they are collected.

The combustion experiments in the domestic pellet stove were repeated three times for each type of pellets.

Classical one-way ANOVA computations were performed on two combustion characteristics (exhaust temperature and CO emissions) for the three combustion experiments of each type of pellets with a significance level of 5%. In complement, separation of the means of these combustion characteristics obtained for the three combustion experiments were performed using Fisher's Least Significant Difference (LSD) through Minitab software, as in [8].

2.2.2. Gaseous emissions

To determine the amounts of the main emitted gases, two gas analyzers Rosemount NGA 2000 were used with the following detection methods: O_2 (paramagnetic), CO, CO_2 and NO (infrared) and NO_2 and SO_2 (ultraviolet). According to NF EN-303-5 [37], the gas concentrations expressed in mg/Nm^3 were referred to 13% of O_2 in the exhaust tube to ensure comparison between the combustion experiments.

2.2.3. Total Suspended Particles

The TSP amounts were measured by a gravimetric method according to DIN CERTCO regulation [38]. A glass fiber of A/E type (without binder, aerosol retention at 0.3 µm DOP is 99.98 %) was placed in a derivation of the exhaust tube during 30 minutes. The fume sample collection flow rate was controlled and maintained at 0.5 Nm³/h. The mass of TSP collected on the filters was calculated by difference of the weights of the filter before and after the combustion experiment using a laboratory balance with an accuracy of 0.1 mg.

2.2.4. Combustion efficiency

The combustion efficiency was calculated using the following formula (DIN EN-13240 2001) [38], see also the supplementary material, section S1, for further details:

$$\eta = 100 - q_A - q_B - q_r, \qquad (2)$$

where:

- q_A is the flue gas loses (%), which were calculated using Siegert's equation:

$$q_A = \frac{(T_c - T_a) \times \dfrac{C_{pmd} \times (C - C_r)}{0.536 \times (CO_2 + CO)} + \dfrac{C_{pmH_2O} \times 1.92 \times (9H + W)}{100}}{NCV}, \qquad (3)$$

where T_c being the flue gas temperature (°C), T_a the ambient temperature (°C), C_{pmd} the specific heat of dry flue gas in standard conditions (depending on the temperature and the composition of gases, kJ/K.m³), C the carbon content of the fuel (%), C_r the carbon content of the residue (%), CO_2 the CO_2 concentration in the flue gas (%), CO the CO concentration in the flue gas (%), C_{pmH_2O} the specific heat of water vapor in flue gases in standard conditions (depending on the temperature, kJ/Km³), H the carbon content of the fuel (%), W the moisture content of the fuel (%) and NCV the net calorific value of the pellets (MJ/kg),

- q_B is the proportion of the losses through latent heat in the flue gases, given through:

$$q_B = 100 \times \frac{12644 \times CO \times (C - C_r)}{(0.536 \times (CO_2 + CO) \times 100) \times NCV}, \qquad (4)$$

- q_r is the proportion of the heat losses through unburnt constituents in the residues, given through:

$$q_r = \frac{335 \times b \times R}{NCV}, \qquad (5)$$

b being the combustible constituents in the residues referred to the mass of residues (% of mass) and R meaning the residues passing through the grate (% of mass).

The oxygen excess λ_O, the air factor λ, the air-fuel ratio and the heat output P were calculated through classical formulas, which are also gathered in the supplementary material, section S1.

3.   Results and discussion

3.1.   Combustion efficiency

Pellets were introduced in the pellet stove with a flow approximately equal to 1.6 kg/h. This flow was then corrected through the formula:

$$Corrected\ flow = flow \left(1 - \frac{ash_{550}}{100}\right), \qquad (6)$$

taking into account the ash amount measured at 550 °C.

The values of different experimental parameters are indicated in Table 5 for the combustion of Cameroonian and EN+ pellets.

Table 5

Values of the ambient and exhaust temperatures, of the adjusted P-value as deduced using Minitab, of the remaining ash at 550 °C, of the corrected flow, for the three types of Cameroonian pellets

and for EN+ pellets [31].

Sample	Ambient Temp. (°C)	Exhaust Temp. (°C)	Adjusted P-value	Ash at 550 °C (%)	Corr. pellet flow (kg/h)
30/60/10	24.8±0.0	170.6±0.7a	0.0	3.0	1.7
60/30/10	25.3±0.1	174.6±0.4b	0.0	4.0	1.6
45/45/10	25.5±0.1	169.3±7.1c	0.0	3.3	1.5
EN+	25.5	189.0		0.3	1.7

The letters added in the column of the exhaust temperature being different for each sample indicate that the means are significantly different according to Fisher's LSD (P≤0.05).

The exhaust temperature is higher for the combustion of EN+ pellets than that for the combustion of the three Cameroonian ones, possibly because of a more complete combustion in the case of EN+ pellets.

ANOVA computations on the exhaust temperature with a significance level of 0.05 revealed very significant differences of the mean values of the exhaust temperatures between the three combustion tests for each type of Cameroonian pellets (550 times the critical threshold associated to a significance level of 0.05). The main reason is the presence of oscillations in the combustion characteristics even in the steady regime, these oscillations being highly amplified by the number of points (times) which are considered in the ANOVA computations. For example, the standard deviations of the exhaust temperature represents at most 4.2% of the mean temperature (for the 45/45/10 pellets). These quite small variations are distributed along the overall steady regime observation. Fisher's LSD group comparisons prove that the means of the exhaust temperatures for the three samples are significantly different.

3.2. Combustion efficiency

According to the computations presented in section 2.2.4, the combustion of the Cameroonian and EN+ pellets leads to the values of the combustion efficiency gathered in Table 6, taking an air excess of 15%, see section 2.2.

Table 6

Values of the combustion efficiency for the three types of Cameroonian pellets and for EN+ pellets [31].

Sample	Air factor λ	Air-Fuel ratio	Efficiency η (%)	Heat output P (kW)
30/60/10	5.0	27.5	68.5	5.9
60/30/10	3.0	17.6	80.2	6.9
45/45/10	3.4	19.3	78.1	6.7
EN+	3.9	19.3	78.2	6.2

The air factor is high for the combustion of each type of pellets, which proves that the combustion experiments took place under a high air excess in the fume. Consequently, the air/fuel ratio is also very high in the four cases. The combustion of the 30/60/10 pellets occurred with an air excess higher than that of the other pellets, which explains the lower efficiency and the lower heat output obtained for these pellets.

Except for the 30/60/10 pellets, the heat output approximately reaches the nominal power of the stove. This heat output is higher for the 60/30/10 and 45/45/10 pellets than for the EN+ and 30/60/10 ones.

Even if the stove behavior was optimized for the combustion of EN+ pellets, the characteristics of

the combustion of the 60/30/10 and 45/45/10 Cameroonian pellets are not very far from or slightly higher than that of the EN+ pellets.

Considering only the values of the combustion efficiency, it seems better to consider pellets made with a proportion 60/30/10 of the three base materials as it gives the highest combustion efficiency and the higher heat output.

3.3. Gaseous emissions

Table 7 gives the average values of gas concentrations together with their standard deviations, for the three Cameroonian and the EN+ pellets [31].

Table 7

Values of the gaseous emissions (% or mg/Nm^3), and of the adjusted P-value as deduced using Minitab, for the three types of Cameroonian pellets and for the EN+ pellets (corrected at 13% O_2 in the fume).

Sample	O_2 (%)	CO (mg/Nm^3)	Adjusted P-value	CO_2 (%)	NOx (mg/Nm^3)	SO_2 (mg/Nm^3)
30/60/10	14.7±1.3	648±537a	0.0	5.2±1.1	224±26	0±0
60/30/10	13.9±0.5	546±219b	0.014	6.0±0.5	207±8	43±13
45/45/10	14.7±0.8	543±190c	0.0	5.2±0.7	229±18	35±12
EN+	15.7±0.1	193±12		5.9±0.1	0.040±0.002	nd[a]

[a]: not determined

The letters added in the column of the CO concentration being different for each sample indicate that the means are significantly different according to Fisher's LSD (P≤0.05).

Again, ANOVA computations on the CO emissions with a significance level of 0.05 revealed significant differences of the mean values of the CO emissions between the three combustion tests for each type of pellets (18 times the critical threshold associated to a significance level of 0.05). High variations of the CO emissions are observed for the three combustion tests which can explain such results. Fisher's LSD group comparisons prove that the means of the CO emissions for the three samples are significantly different.

The combustion of 60/30/10 pellets leads to the lowest NOx and (almost) CO emissions. However, it leads to the highest CO_2 and SO_2 emissions. This suggests that the combustion of the 60/30/10 pellets is slightly more complete.

The highest CO emissions were obtained for pellets containing the maximal PNF proportion (30/60/10), the base material which contains the largest amount of potassium, see Table 3. Potassium is known to enhance the degradation of biomass and especially of its cellulose component [39-40]. It indeed largely favours the gasification of cellulose with an increase of gaseous species, mainly incomplete combustion gases as H_2, CO. In [40], the authors proved that the ring-opening of C-O-C cellulose bonds was enhanced by the addition of K_2CO_3 with the emission of light hydrocarbon molecules. Schmidt et al. showed that the reduction of potassium from woody biomass samples by the leaching process could disfavour the pyrolysis mechanism of saccharide polymers during the starting phases of the thermal treatment leading to lower CO concentrations in the exhaust [31].

The NOx emissions represent the sum of NO and NO_2 and mainly consist of NO, the NO_2 emissions being lower than 3 mg/Nm^3 for Cameroonian pellets.

The SO_2 emissions are low, whatever the pellets and are not detectable during the combustion of the 30/60/10 pellets. The NOx and SO_2 emissions can be correlated with the percentages of

elemental N and S in the base materials, see Table 1, which shows that PNF has the lowest percentages of N and S.

In comparison, the combustion of EN+ pellets leads to much lower CO emissions (ratio equal to 2.5 or 3.3) and NOx emissions (ratio equal to 2.6 or 2.8). However, according to the French label "Flamme verte", French pellet stoves are optimized for the use of normalized EN+ pellets with demanding requirements for the efficiency, pollutant emissions and nominal heat output.

In [17], the NOx emissions were measured between 25 and 340 mg/Nm^3, quite in the same range as in the present study. The maximal SO_2 emissions were measured between 75.9 and 245.6 mg/Nm^3, for all pellets except that made with wheat, much higher than in the present study.

The CO concentration was measured in homes equipped with a three-stone-fire stove in Adamawa, Cameroon, at 29.5 ppm at most (47 mg/Nm^3) [1]. This is far below the highest corrected particulate matter concentration (476 mg/Nm^3) which is obtained in the present experiments. However, in the present experiments, the CO emissions were measured in a derivation of the exhaust tube, while in [1] the CO emissions were measured in the indoor air during 24 hours. No other gaseous emissions were measured in this study. The gaseous emitted during the combustion of Douglas fir in different stoves similar to that which can be used in Cameroon are analyzed in [25] using a portable monitoring emission system from APROVECHO. The CO emissions collected during the whole combustion experiment were measured between 17 and 85 g, depending on the stove and on the fuel moisture.

3.4. Total Suspended Particles emissions

Table 8 gathers the amounts of TSP collected in the filter (mean value and standard deviations of the three experiments).

Table 8

Values of TSP during the combustion of Cameroonian and EN+ pellets [31] (corrected at 13% of O_2 in the fume).

Sample	TSP (mg/Nm^3)	TSP (g/kg)
30/60/10	130±50	2
60/30/10	240±40	7
45/45/10	160±30	3
EN+	35±8	1

The French label Flamme Verte 7 stars imposes an upper limit of 40 mg/Nm^3 for the TSP emissions. The combustion of the pellets 60/30/10 presents the highest TSP emissions (ratio equal to 1.8 or 1.5). The TSP emitted during the combustion of Cameroonian pellets are much higher than the French standards (ratio 3.3 to 6) and than that emitted during the combustion of EN+ pellets. The combustion of Cameroonian pellets does not comply with the demanding requirements concerning the gaseous and particulate emissions in France or European countries. One reason is that the combustion of Cameroonian pellets is more incomplete than that of EN+, see also the amounts of CO in the fume as presented in Table 7. These Cameroonian pellets were very brittle, which surely increases the possibility for particles to fly away during the combustion. Consequently, the TSP concentrations in the flue gas are high during the combustion of Cameroonian pellets due to the presence of both particles from pellets and fly ashes.

Values of the TSP emissions from the combustion of Cameroonian pellets are not available in the literature. As the TSP mass distribution mainly contains fine particle, data concerning fine particulate matter $PM_{2.5}$ can give an idea of the amount of TSP emitted during the combustion of

Cameroonian pellets. The $PM_{2.5}$ concentration measured in homes equipped with a three-stone-fire stove in Adamawa, Cameroon, reach at most 5494 µg/m^3 [1]. This is far below the highest corrected particulate matter concentration (2.4×10^5 µg/m^3) obtained in the present experiments. However, in the present experiments, the overall TSP were collected in a derivation of the exhaust tube, while in [1] the $PM_{2.5}$ were collected from the indoor air during 24 hours. In [25], the particulate matter emitted during the combustion of different stoves was collected using APROVECHO's PM meter utilizing light scattering. The amounts were measured between 0.5 and 2.9 g/kg, during the whole combustion of Douglas fire, depending on the stove and on the fuel moisture. Even if the experimental conditions are totally different between that of [25] and that of present study, the values of TSP collected in a derivation of the exhaust line and indicated in Table 8 lie in the same range.

4.   Conclusion

Combustion experiments of pellets made with three Cameroonian forest- and agro-indutrial waste (Palm nut shell, Palm nut fiber, Coffee Husk) in three different proportions were performed in a domestic pellet stove. The combustion efficiency was found in almost the same range as that obtained with EN+ pellets burnt in the same pellet stove. The gaseous and particulate emissions measured in a derivation of the exhaust tube during the combustion of these Cameroonian pellets were higher than that obtained when burning EN+ pellets in the same pellet stove. The pellets in the proportions 60/30/10 gave the highest combustion efficiency and heat output, but these pellets produced the highest TSP amounts during their combustion, which could be attributed to the brittle property of the Cameroonian pellets. The two other Cameroonian pellets considered in the present study may also be considered as a suitable biofuel for combustion in a domestic pellet stove.

Because the behavior of the stove which has been used in the present study was optimized for EN+ pellets, a further study would consist to adapt the characteristics of the stove for such Cameroonian pellets, to get a more complete combustion. Cameroon and more generally sub-Saharan countries produce other forest- and agro-industrial waste which could also be considered as biofuels for cooking purpose at a domestic scale. The determination of an optimal formulation of the pellets to be burnt is to be considered. Further steps will consist to build a low-cost domestic stove, which improves the traditional three-stone-fire cookstove and to determine an optimized combustion process of the locally produced pellets [41]. This would use locally available forest- and agro-industrial residue in a circular economy.

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