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Performance and emissions characteristics of compressed spent coffee ground/wood chip logs in a residential stove

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ABSTRACT

Spent coffee grounds (SCG), a processing by-product from the soluble coffee industry, was evaluated as a potential feedstock for preparing compressed logs for energy production. Hence, a blend of SCG/wood chips was transformed into densified logs using an industrial press. Chemical properties such as calorific value, ash content and elemental analysis were obtained. Combustion tests were carried out with a five-star–labeled stove in a French industrial research and development laboratory. Three different configurations were tested: a densified log containing 20 wt% of SCG blended with pine wood chips, another containing a mixture 50/50 wt% of SCG/pine wood chips and a classical beech log. This study is the first one that focuses on the potential of compressed logs as a new biocombustible for wood stoves. The obtained results show that the combustion of logs containing SCG leads to better yield of combustion. Nevertheless, CO and particle emissions increase when increasing the rate of SCG although the exhaust gas emissions and combustion yields always lead to the "five-star Flamme Verte" label achievement. Such attainment is essential to sell these densified biofuel logs in the French market. Results indicate that the blended densified logs are combusted rapidly leading to higher stove efficiency and therefore good heat recuperation from the stove walls. On the contrary, the addition of SCG leads to lower CO_2 concentrations (7.7% and 9.05% for 20 wt% and 10 wt% of SCG, respectively). This behavior indicates that the combustion of compressed logs is not suitable for the stove design and may lead to an uncomfortable heating. One should be reminded that the evaluated stove was designed for the combustion of conventional wood logs (with respect to the *NF Bois de Chauffage* standard). This means that the results obtained during this study with the different densified fuel logs could be improved after an adjustment of the stove conception.

Introduction

The depletion of fossil fuels and the enhancement of the greenhouse effect have driven many industries to use renewable resources for energy purposes (McKendry, 2002a). Therefore, the energy recovery of biomass via pyrolysis, combustion and gasification has gained worldwide serious attention (McKendry, 2002b). Among these thermochemical conversions, combustion technologies are highly developed at different scales. Nevertheless, a significant part of biomass combustion is realized in fireplaces and domestic stoves, which are used in considerable numbers.

In France, domestic heating represents 71% of wood primary energy consumption (7.4 Mton/year). In fact, 6 million houses are currently heated using wood combustion appliances; this represents 23% of the houses in France (50% of the individual houses). Among these combustion devices, wood stoves and fireplaces are the most commonly used for space heating in homes. During the last decades, tax incentives in France (tax refunds for investment in renewable energy increased from 15% to 50%) have led to an increase of the number of wood combustion devices sold from 250,000 in 1999 to 467,355 in 2011. A detailed inventory in 2011 revealed that stoves represent about 56.3% (263,285 apparatus) and fireplaces about 42.3% (197,750 apparatus) (Suivi du marché, 2011). These numbers will continue to increase since the energy policy in France aims to reach 9 million households equipped with wood combustion appliances by 2020.

For heating purposes, biomass sources are mainly wood fuel and wood products. In France, 50 million m^3 of wood are annually consumed in which wood logs represent more than 95% from the total wood market. The wood logs have several advantages since they are considerably cheaper and are available in huge amounts. However, their moisture content is much higher and they require space to stack and to dry before use. Generally, drying wood should be stacked on bearers in a sunny, windy location, ideally under some form of waterproof cover with open sides. Many stove manufacturers often specify 20% moisture content or less, and this is likely to take two summers or more to be achieved by air drying. Recently, particular interest has been given to compressed logs with an annual consumption of 50,000 tons. The main advantages are the lower moisture content and

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their easier storage. Currently, several fuel producers have claimed that their compressed logs are one of the cleanest forms of heat available in the world today, providing more heat, less work, less handling and less maintenance [www.homefirelogs.com]. Whereas there is much data about the operating conditions and gaseous emissions of wood log stove, there is no data available on the combustion behavior and flue gas composition of compressed logs.

Compressed logs are essentially produced through the compacting of wood sawdust. However, the development of the domestic heating market should be followed by the identification of new biomass sources. Currently, several biomass residues face several problems, which limit their wider application for power generation. In fact, several biomass sources such as sawdust, spent coffee grounds, rice straw, olive solid waste and sugarcane bagasse have high moisture content, low bulk density, low heating value, low ash melting point and their use is not economically viable (Demirbas, 2004; Jenkins et al., 1998). Therefore, several options were proposed to prevent these drawbacks such as biomass densification and mixing with more suitable fuel such as sawdust (Reza et al., 2012; Lehtikangas, 2001). Several researchers have investigated the production of different pellets from various agro-residues such as rice husk, coconut shell and coconut fiber; energy crops such as miscanthus; and cereal straws such as rape straw, barley and wheat straw (Liu et al., 2014; Carroll and Finnan, 2012). Therefore, the suitability of these agropellets for small-scale heat and power generation using direct combustion was examined (Nunes et al., 2014). The main investigations have evaluated the performance of these biofuels in domestic pellets boilers and compared them with the different European standards (Nunes et al., 2014; Kraiem et al., 2014; Fournel et al., 2015; Miranda et al., 2012; Cardozo et al., 2014). However, to our knowledge, the development of biofuels from agro-residues and agro-industrial residues for domestic stoves and fireplaces is scarce and has not received any particular attention.

Among the various agro-industrial residues, spent coffee grounds (SCG), the main coffee industry residues, are generated in large amounts. These residues are toxic due to the presence of caffeine, tannins and polyphenols (Mussatto et al., 2011). SCG are the solid residues collected during the instant coffee preparation from the coffee powder treatment with hot water. SCG consists mainly of fine particle size with higher humidity (in the range of 80% to 85%) and organic load (Mussatto et al., 2011).

Several attempts were performed for the energy recovery of the coffee residues (Saenger et al., 2001). Kondamudi et al. showed that SCG can be used for biodiesel and fuel pellets production (Kondamudi et al., 2008). Recently, the potential of SCG as a precursor for preparing biochar fuel was examined (Tsai et al., 2012). The authors have shown that the obtained biochar may replace coal as solid fuel in the industrial sector (Tsai et al., 2012).

Recently, pellets (d = 6–8 mm, L = 3.5–40 mm) were prepared from spent coffee grounds (SCGs)/pine sawdust blends according to the French agropellets standard. The performance of these pellets was tested in a domestic pellets combustor. Combustion tests have shown that the boiler performance was very close to the one obtained for wood pellets. Hence, the densification of SCG with pine sawdust may be an interesting valorization route for SCG coffee residues (Limousy, 2012).

In France, combustion devices using pellets represent less than 10% of the total market of biomass domestic heating. Hence, it seems necessary to develop a biofuel from coffee residues for stoves and fireplaces. Therefore, the aim of this current study is to develop logs from spent coffee grounds and wood chips mixture. The performance and the gaseous emissions of the produced logs are examined during combustion tests using residential stoves. The main purpose is to evaluate the possibility of these biofuels to reach the French standards in order to commercialize these logs in the French market. The French market for compressed fuel logs corresponded to 50,000 tons in 2013 and it was close to 100,000 tons in 2014. This means that there is a good opportunity to develop new compressed fuel logs from alternative biomasses, considering that the use of wood chips and sawdust will be more and more complicated. In fact, the wood resource remains the same year after year, but the demand as well as the price increases continuously. Hence, the use of SCG in compressed logs could be a promising alternative since 600,000 tons are generated each year in France. Among these generated residues, about 200,000 tons could be easily collected and therefore available for compressed logs and pellets production.

In addition, improving knowledge on the operating conditions and flue gas composition of the current wood stove when using compressed logs as fuel is an important challenge. In fact, such a study will help to achieve an efficient, economic and environmental biomass combustion and to offer the identification of innovation opportunities. This original study is the first one being devoted to the adaptability of compressed logs to conventional wood stoves. At the moment, there is no study concerning the combustion of compressed logs as well as their potential as new biocombustibles for wood stoves.

Materials and methods

Log preparation

SCG residues were furnished by a coffee processing plant (Brûlerie d'Alre, Auray, France), and wood chips were provided by a French sawmill using wood pine. The conventional beech logs were purchased from a local wood wholesaler. These logs are 300 mm in length, contain less than 20 wt% of humidity, which corresponds to an H1–G1 classification in the "NF bois de chauffage" label. This French label classifies fuel wood logs according to their species (G class) and their humidity ratios (H class). Hence, the G class of wood logs is divided into two groups of species, depending on the amount of heat supplied per unit volume. The class G1 includes oak, hornbeam, beech, European ash and maple while the class G2 includes chestnut, black locust, birch, cherry and various fruit trees. The H class includes H1 for fuel wood humidity lower than 20% (wet basis) while H2 for fuel wood humidity higher than 20% (wet basis).

The elemental analysis of SCG, pine wood chips and beech is summarized in Table 1. Table 1 shows that the SCG ultimate analysis is different from the ones found in the literature for woody biomasses (Limousy, 2012; Jeguirim et al., 2014; Pighinelli et al., 2014). Table 1 shows that SCG have a high content of carbon source, which demonstrates that SCG may be used in compressed fuel logs production. However, the higher nitrogen and sulfur contents are limiting compounds for pollutants formation in exhaust gas emission. Hence, blending SCG with pine sawdust may help to reduce such emissions.

Logs production occurs in three unit operations including drying, grinding (size reduction) and compacting (densification). Woody biomass consists of wood chips (Fig. 1), which are dried in a tumble-dryer (Europ Service Industrie, Vernouillet, France) until the moisture reaches a value of 12% (±2%) (Fig. 2a).

The same procedure is applied to SCG. Inlet air temperature is set at 400 °C, outlet wet air leaves the dryer at approximately 70 °C, and the residence time of wood chips or SCG is close to 25 min. After drying, wood chips are ground with a hammer grinder (Europ Service Industrie, Vernouillet, France), and then sieved in order to have wood chips with a distribution size between 6 and 20 mm. The grinder consists of a grid of 1 m^2 equipped with eighty hammers, and has a capacity of 3 tons/h. This

Table 1
Ultimate analyses of initial samples.

Sample	% C	% H	% O	% N	% S	% Ash
SCG	61.1	9.0	26.6	2.9	0.4	1.9
Pine	47.6	6.1	46.0	<0.1	<0.01	0.3
Beech	49.3	5.8	44.2	<0.1	<0.01	0.6

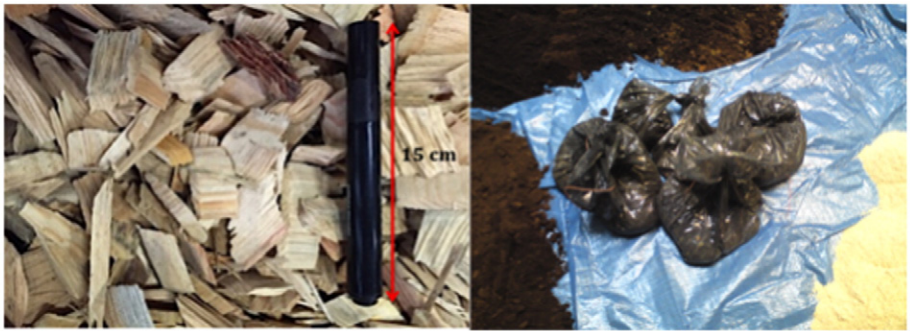

Fig. 1. Left picture, typical wood plates (before grinding) used for the preparation of the densified wood logs. Right picture, conditioning of spent coffee grounds coming from automatic vending machines.

operation is very important in order to obtain a good size distribution of wood chips necessary to give high mechanical resistance to the compressed logs, even when they contain 20% of spent coffee grounds. Pure wood chips or a blend of SCG (20% wt) and wood chips (80% wt) are injected into the log maker (NIELSEN) (Fig. 2b).

The pressure log maker has a capacity of 1.5 tons/h and operates at a temperature of 120 °C and a pressure of 2 tons/cm^2. The process leads to the formation of logs with a 90 mm diameter and 300 mm length approximately after cutting out with a circular saw (Fig. 3). Logs are not directly packed because they are still hot when leaving the log maker. In fact, packing up could lead to the formation of moisture at the surface of the plastic film when the logs are immediately wrapped. Hence, packing up is done the next day when the logs are at room temperature.

Combustion tests

Combustion devices and measurements

The combustion experiments were carried out with a cast-iron wood stove (Lorflam, XP68) at the test bench of the Lorflam Company (Caudan, France) (Fig. 4). The combustion chamber has an approximate volume of 0.075 m^3 (0.58 m length, 0.37 m height and 0.35 m depth). It is operated manually in batch mode with manual control of combustion air. The primary air comes from the front of the stove and penetrates the combustion chamber by the grate (just under the fuel).

Combustion tests were performed with an initial forced draught (12 Pa of pressure drop) wood stove with a nominal heat output of 8–12 kW exclusively prepared for combustion tests. This stove is supplied with an air extractor (variable speed), which allows the control of the starting pressure drop. It was employed at nominal power with an initial draught of 12 Pa, which lead to an initial exhaust gas flow close to 28 m^3/h. The stove was installed in a scale (Sartorius, France) with 1 g precision. The outlet temperature of the exhaust gas, as well as fuel mass loss were continuously monitored.

In each cycle, four logs were combusted in the domestic stove. The total load ranged between 1.8 and 2.4 kg (wet basis). This total load was calculated according to the European Standard NF EN 13229 dedicated to the requirements and test methods for stoves fired by solid fuels and using the following equation:

$$B = \left[\frac{360{,}000 \times P_n \times t_b}{LHV \times \eta_{th}}\right] \tag{1}$$

where

- B: mass of fuel requested for the combustion test (kg)
- LHV: low heating values (kJ/kg) (wet basis)
- P_{n}: nominal power (kW)
- t_{b}: the interval or minimum recharge time, as stated by the manufacturer (h)
- η_{th}: minimal device efficiency requested by the standards or value specified by the manufacturer (%)

During the log combustion tests, different data were collected including: (i) fuel mass on the grate and fuel consumption rate, (ii) temperature profiles of the flue gas at the chimney exit, (iii) combustion gas flow rate and (iv) flue gases composition (CO_2 and CO) at the chimney exit.

Gaseous emission measurements

Gaseous emissions were measured using different specific analyzers (COSMA Crystal 300 0%–1% for CO, and ROSEMOUNT Binos 100 0%–10% for CO_2) for 45 min directly after the introduction of the tested fuel. The combustion experiments were carried out when the boiler was operating at a stabilized temperature obtained after a complete combustion assessed with 2 kg of wood logs (0.5 kg of remaining embers on the stove grid). According to French standards, carbon monoxide (CO) and carbon dioxide (CO_2) emissions were recorded during combustion tests. Gas sampling was continuously realized through the exhaust gas manifold with respect to the NF EN 304 standard at constant flow (close to 1 L/min). Particle

Fig. 2. Pictures of the (a) industrial tumble dryer and (b) the log maker (NIELSEN) equipped with a maintenance rail and a circular saw.

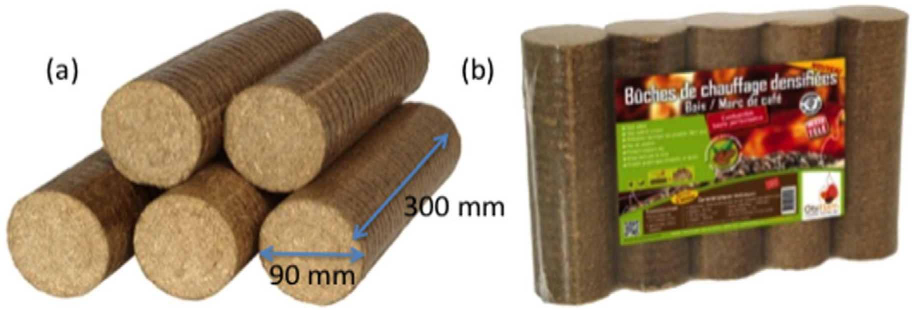

Fig. 3. (a) Commercial wood logs obtained after compression of pure pine chips and cutting out at standard dimensions. (b) Commercial compressed logs containing both pine chips and spent coffee grounds.

concentration was estimated according to the empirical relation "corrélation CO — Poussières" (ADEME, 2011):

$$[\text{Particles}] = 42.134e^{(3.5536\times[\%\text{CO}])}\,\text{mg Nm}^{-3} \qquad (2)$$

Since 1 January 2013, the correlation "CO — Poussières" no longer applies to new appliances. Therefore, it is requested to perform particle measurements for new devices during laboratory tests.

Performance measurements

The stove efficiency was calculated from the results obtained during different combustion tests. The calculation was performed using the NF EN 13 229 standard related to stoves. This standard calculation is based on the valuation of sensible heat losses (q_a kJ/kg) and chemical energy losses (q_b kJ/kg) in the flue gas. The percentage of heat loss due to combustible constituents in the residue is taken to be equal to 0.5% for logs. Sensible heat losses come from both energy present in the dry flue gas (Eq. (3)) and also from energy stored by steam (Eq. (4)).

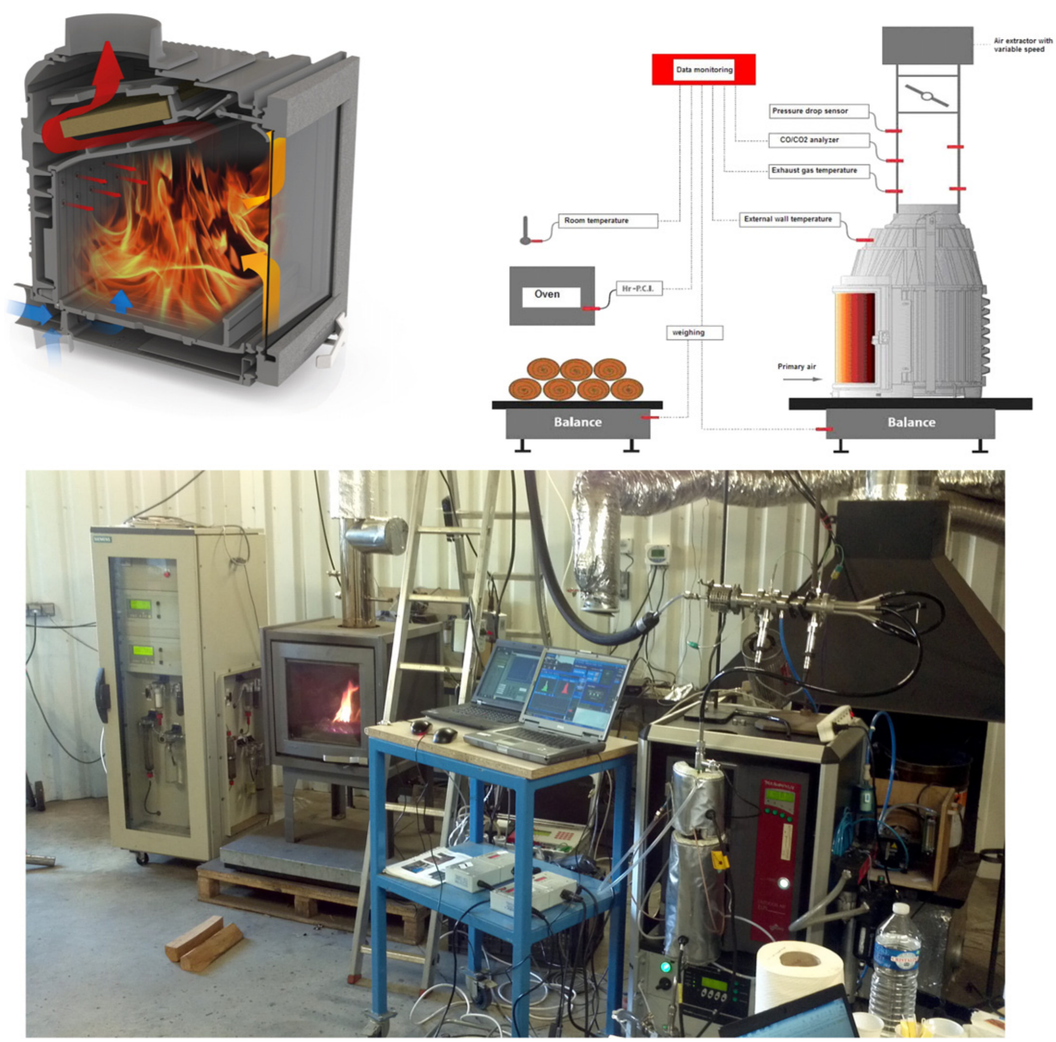

Fig. 4. Primary and secondary air distributions in the XP68 stove (top left picture), synoptic scheme (top right picture) and experimental laboratory setup (last picture) used for the combustion tests.

Heat losses coming from the dry flue gas are estimated as follows (q_1):

$$q_1 = C_{pmd} \times V_{dryfluegas} \times \Delta T \tag{3}$$

$$q_1 = C_{pmd} \times \left(\frac{(C - C_r) \times \frac{22.4}{12}}{CO + CO_2} \right) ((T_g - T_a)) \tag{3}$$

$$q_1 = C_{pmd} \times \left(\frac{C - C_r}{0.536 \times ((CO + CO_2)} \right) ((T_g - T_a)) \tag{3}$$

Heat losses coming from steam are estimated as follows (q_2):

$$q_2 = C_{pmH_2O} \times V_{H_2O} \times \Delta T \tag{4}$$

$$q_2 = C_{pmH_2O} * \left(\frac{22.4}{18} \left(\frac{W}{100} + \frac{9H}{100} \right) \right) \times (T_g - T_a) \tag{4}$$

$$q_2 = C_{pmH_2O} \times \left(1.244 \left(\frac{W}{100} + \frac{9H}{100} \right) \right) \times (T_g - T_a) \tag{4}$$

Then, sensible heat losses correspond to the sum of q_1 and q_2 and are expressed by Eq. (5):

$$q_a = (T_g - T_a) \times \left[\left(\frac{C_{pmd} \times (C - C_r)}{0.536 \times (CO + CO_2)} \right) + \left(C_{pmH_2O} \times 1.244 \times \left(\frac{9H + W}{100} \right) \right) \right] \tag{5}$$

Energy losses (q_b) are estimated from the incomplete oxidation of CO present in the flue gas. The calculation of q_b is described by Eq. (6) as follows:

$$q_b = \text{(energy loss corresponding to the non-oxidation of CO into } CO_2) \times \text{(volume of CO produced during the combustion of the fuel)} \tag{6}$$

$$q_b = \Delta H^{\circ}_{CO->CO_2} \times \frac{CO}{100} \times V_{dryfluegas} \tag{6}$$

$$q_b = \frac{12,644 \times CO \times (C - C_r)}{0.536 \times (CO + CO_2) \times 100} \tag{6}$$

where

- $V_{\text{dry flue gas}}$ corresponds to the volume of dry gas emitted during the combustion (m^3)
- V_{H2O} corresponds to the volume of steam produced from moisture and hydrogen present in the fuel (m^3)
- T_g and T_a are the exhaust gases and air temperatures (K).
- C_{pmd} and C_{pmH2O} are the specific heats of dry flue gases and water vapour (kJ/K.m^3).
- CO and CO_2 are the contents in the dry flue gases (% of volume).
- C_r is the carbon content of the residue passing through the grate (% of original fuel mass) = 0.5%
- C is the carbon content of the tested fuel (% of mass on wet basis).
- H is the hydrogen content in the tested fuel (% of mass on wet basis)
- W is the moisture content in the tested fuel (% of mass on wet basis)
- $\Delta H^{\circ}_{CO->CO_2}$Z corresponds to the heat release of oxidation of CO into CO_2 (kJ.m^{-3})

Table 2
Description of the environmental performance obtained according to the I index value with the ADEME system.

I_{logs} intervals	$0 \le I \le 1$	$1 < I \le 2$	$2 < I \le 3$	$3 < I \le 4$	$4 < I \le 5$
Device performance class	★★★★★	★★★★	★★★	★★	★

The combustion efficiency (η%) is finally calculated:

$$\eta = 100 - \left(\frac{q_a + q_b}{LHV} \right) \times 100 - 0.5 \tag{7}$$

- LHV corresponds to the low heating values on wet basis (kJ/kg)

As mentioned previously, the value 0.5 in Eq. (7) corresponds to the percentage of heat loss due to combustible constituents in the residue. This value is estimated since it is it is not possible to obtain the correct percentage of unburnt carbon in the ash at the end of the combustion tests. In fact, to perform a combustion test, the stove must contain a certain amount of embers corresponding to about 5% of the fuel used to pre-heat the stove.

Description of the Green Flame French label

In 2000, the French Environmental and Energy Control Agency (ADEME) and stove manufacturers started the Green Flame label in order to incite manufacturers to improve the efficiency of stoves, from an environmental and an energetic point of view. Manufacturers take advantage of this label because customers get money back from the French government when they buy a green flame–labeled stove (30% discount). For stoves, the Green Flame label is given when CO emissions observed during a standard combustion test (see standard NF EN 13 229 presented above) are below 0.3% vol, and when the yield of combustion exceeds 75% (2015 levels). Then, another parameter I (performance index) is determined from the calculation of an index (I or I'), which is specific to the fuel shape (logs or pellets) and also to the emissions of CO and particles (both corrected at 13% O_2) (ADEME, 2011).

The value of the index I defines the environmental performances of the combustion device as described in Table 2. This index is calculated from the empirical Eq. (8) where E corresponds to the CO concentration (%) at 13% O_2 and η to the yield of combustion (%).

$$I_{\text{logs}} = \frac{101532.2 \times \log(I + E)}{\eta^2} \tag{8}$$

If the value of I_{logs} corresponds to the 5-star class, then a new calculation must be achieved in order to take the particle emissions into account. The new index I' is predominantly behind the I value and is used to determine the final class of the combustion device. I' value is assessed by Eqs. (9), (10) and (11) where CO_{eqPM} is CO equivalent amount calculated from the PM concentration (mg/Nm^3) calculated from the “CO — Poussière” correlation (Eq. (2)) or measured by a PM analyzer.

$$I'_{\text{logs}} = \frac{101532.2 \times \log(I + E')}{\eta^2} \tag{9}$$

$$E' = \frac{(CO + CO_{eqPM})}{2} \tag{10}$$

$$CO_{eqPM} = 0.002 \times PM \tag{11}$$

Since 1 January 2015, two new classes of quality (6 and 7 stars) were introduced. The difference with the five-star class corresponds to the maximal concentration of particles, which must not exceed 50 mg.Nm^{-3} and 40 mg.Nm^{-3} for the 6- and 7-star classes, respectively. In the present study, the used stove (Lorflam XP68) is five-star labeled. Lorflam Company obtained this label from tests performed in an accredited private laboratory.

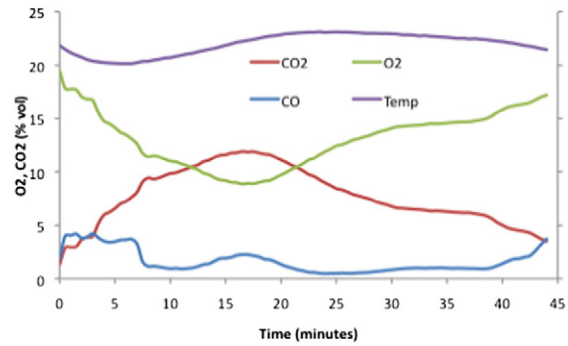

Fig. 5. CO_2 (%), O_2 (%), CO (%) and temperature (°C/100) profiles observed during the combustion of a SCG (20%)/pine sawdust (80%) log (1.8 kg), following the French normalized test (45 min) (uncorrected experimental values).

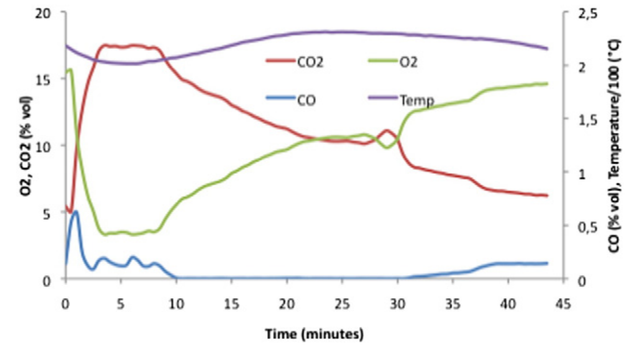

Fig. 7. CO_2 (%), O_2 (%), CO (%) and temperature (°C/100) profiles observed during the combustion of a beech wood log (2 kg), following the French normalized test (45 min) (uncorrected experimental values).

Results and discussion

Log characteristics

The ash and moisture contents were determined in agreement with CEN/TS 14775 (Solid biofuels: Method for the determination of ash content) and CEN 14774-3 (Solid biofuels: Methods for the determination of moisture content. Oven dry method: Moisture in general analysis sample) standards, respectively. The ash content is determined by calculation from the mass of the residue remaining after the sample is heated in air under rigidly controlled conditions of time, sample weight and equipment specifications to a controlled temperature of 550 ± 10 °C (EN 14775 & Solid biofuels - Determination of ash content, European Standard.). During the moisture content determination, the biofuel sample is dried at a temperature of 105 ± 2 °C until a constant mass and the percentage moisture calculated from the loss in mass of the test sample (EN 14774–3 & Solid biofuels – Determination of moisture content – Oven dry method – Part 3: Moisture in general analysis sample, European Standard.). The ash and moisture contents as well as the energy contents of the densified logs are shown in Table 3.

It is seen that the blend of coffee residues and pine sawdust is characterized by low moisture contents (10%) because these biomasses were dried before densification, and presents a higher LHV than beech logs. This result is mainly due to the composition of SCG, which presents higher carbon content than wood and, consequently, a greater LHV. Moisture content of beech logs was achieved by natural drying (during 3 years).

Combustion tests

The main aim of this section is to analyze combustion performances and gaseous and particulate emissions of the obtained logs by densification or directly from trees, with a standardized stove XP68 (Green Flame French label: 5 stars).

Figs. 5, 6 and 7 present CO and CO_2 emissions as well as the temperature profile of the exhaust gas obtained during the different combustion tests. The first observation is that the presence of SCG induces a modification of the CO_2 emission profiles. The maximal CO_2 concentration in the exhaust gas is reached after 17 min for the densified logs containing 20 wt% of SCG, while it is necessary to wait 9 min with 10% wt of SCG and 3 min for the test performed with the beech log (Table 4). These results indicate that the maximal rate of combustion is achieved more quickly with classical wood logs than with SCG densified logs. The combustion heat release may also be different; beech wood log combustion leads to a quite constant heat production while the use of SCG induces a more heterogeneous heat release. This observation is correlated with the difference of temperature observed during the combustion tests, which is higher when compressed logs are used (Table 4), while CO_2 concentration decreases. This means that the draught and, consequently, the exhaust gas flow, increases appreciably (dilution of CO_2 in air) when compressed logs were used. The combustion of the compressed logs is also faster than the combustion of the conventional beech logs, with regard to the concentration of CO_2 at the end of the combustion test. Then, the use of SCG may be considered as potentially interesting after some modifications of the stove air distribution system, in order to limit the variation of draught and consequently of airflow entry. This modification may induce a better control of combustion kinetic when using compressed logs.

CO emission profiles also follow an interesting behavior. In fact, an intense peak is observed at the beginning of the combustion for beech logs (1 min, see Table 4) directly followed by multiple peaks of CO with lower concentrations, while two distinct peaks are detected for the tests performed with the blended SCG logs (1 and 7 min for 10 wt% of SCG, and 3 and 17 min for 20% of SCG). The presence of two distinct CO peaks when compressed logs are used can be explained by the difference of combustion behaviors between SCG and wood. The presence of a non-homogeneous (blend of different biomass) fuel induces a shift of the period corresponding to the maximal fuel rate combustion. In each case, the first peak can be attributed to the beginning of the combustion process (cold fuel) and the second to the maximal fuel rate combustion (warm fuel). The maximal concentrations of CO

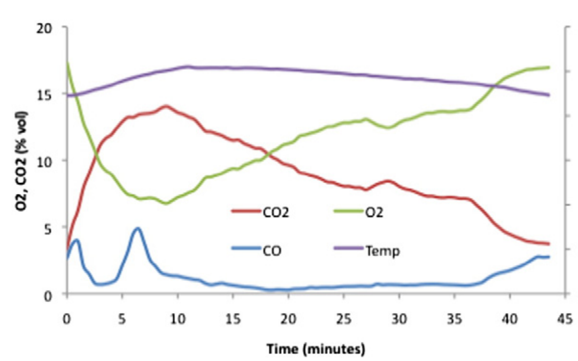

Fig. 6. CO_2 (%), O_2 (%), CO (%) and temperature (°C/100) profiles observed during the combustion of a SCG (20%)/pine sawdust (80%) log (0.9 kg) and a beech wood log (0.9 kg), following the French normalized test (45 min) (uncorrected experimental values).

Table 3
Moisture, ash and low heating values of the different tested logs (wet basis).

Composition and weight of the logs	Moisture – W (%)	Ash (%)	LHV (kJ.kg^{-1})
SCG(20%)/pine sawdust (80%) log (1.8 kg)	10	0.62	17,386
SCG(20%)/pine sawdust (80%) log (0.9 kg) + beech wood log (0.9 kg)	13.5	0.56	15,971
Beech wood log (2 kg)	17	0.49	14,557

Table 4
Uncorrected CO_2 (maximal and final values) and CO (maximal value) gas emissions expressed in % and minimal and maximal exhaust gas temperatures obtained during the combustion tests carried out with the different logs.

Logs	$\%CO_{2\ max}$ (t)	$\%CO_{max}$ (t)	$\%CO_{end}$	T_{min} °C (t)	T_{max} °C (t)	ΔT °C
SCG (20%)/sawdust (80%) log (1.8 kg)	12 (17′)	0.42(3′) 0.22(17′)	3.72	201.6	231.1 (23′)	29.5
SCG (20%)/sawdust (80%) log (0.9 kg) + beech wood log (0.9 kg)	14 (9′)	0.588 (1′) 0.73 (7′)	3.74	222.7	255.1 (11′)	32.4
Beech wood log (2 kg)	17.5 (3–7′)	0.62 (1′)	6.23	248.2	275.1 (15′)	26.9

observed during the combustion tests can't be compared directly while the draught (and consequently air excess) may be significantly different for each combustion tests. CO profiles are representative of the combustion behavior: the higher level of CO concentrations observed when beech logs were used may be explained by a lower draught (this correlates very well with CO_2 emissions: 18% for beech logs, 14% for the mixed logs and 12% for compressed logs) at the beginning of the combustion process compared to compressed logs. However, the combustion kinetic of compressed logs is faster than for beech logs.

Another interesting point corresponds to the exhaust gas temperature increase. The use of densified logs leads to an increase of the specific heat losses estimated from Eq. (6) (2800, 2725 and 2540 kJ/kg for SCG 20 wt%, 10 wt% and 0 wt%, respectively), while the proportion of the thermal heat loss decreases when increasing the SCG content (16.1%, 16.4% and 17.5% for SCG 20 wt%, 10 wt% and 0 wt%, respectively). In fact, the faster the energy is produced, the faster the stove dissipates this energy. This result can be explained by a good capacity of the stove to dissipate the energy produced by fuels with high LHV. The only problem corresponds to the discomfort induced by the specific combustion of the densified logs, which is characterized by a higher heat output and a fluctuating heat release. This means that the temperature increase of air in the room will be faster, and the final temperature of the room will be higher.

Average values of stove efficiencies, the heat output and the exhaust mass flow rates (Eq. (12)) as well as gaseous and particle emissions are shown in Table 5 for each combustion test (emissions are corrected according to an oxygen concentration of 13% by using Eq. (13)).

$$m = \left[\frac{B \times 1.3 \times (C - C_r)}{0.536 \times (CO + CO_2)} + \frac{(9H + W)}{100}\right] / 3.6 \tag{12}$$

$$[\text{Concentration}]_{\text{correctedat}13\%O_2} = [\text{Concentration}]_{\text{Exp}} \times \frac{21-13}{21-[\%O_2]_{\text{Exp}}} \tag{13}$$

where

- m: mass flow rate of the flue gas (g s^{-1})
- B: mass of fuel used for the combustion test per hour (kg h^{-1})

Table 5 shows that SCG addition leads to stove efficiency very close to the one obtained with conventional wood logs. Nevertheless, the increase of the exhaust gas flow rate with the SCG content indicates that the draught depends on the fuel. In fact, the combustion rate of densified logs is higher than that of classical wood logs, and the use of SCG (with a great carbon content) is also responsible of an additional increase of the combustion rate. The main drawback of the densified logs is that their use causes the increase of CO and particle concentrations in the exhaust gas. Better control of the primary air will allow a reduction of the combustion rate, which will then limit the emission of CO and particles.

The results obtained with the beech logs remain in the range of the "five-star Green Flame" limit values (ADEME, 2011). The values of I and I' indexes (described in Section 2.2.4) obtained for each combustion test performed with the different log compositions are presented in Table 6. As expected, the results obtained with the conventional wood logs confirm the label previously obtained by the stove used in this study ("Green flame five stars"). An interesting point is that the results obtained with the densified logs (both with 10 and 20 wt% of SCG) confirm this ranking, and surprisingly, the final ranking obtained with the I' index indicates an improvement of the stove environmental performances while the result obtained with wood logs tends to a higher value. Even if the use of this criterion may be subject of debate, because it was developed in order to qualify combustion devices and not the fuels, it is a potential objective tool to qualify different fuels presenting specific design or composition from classical ones.

Results indicate that the blended densified logs are combusted rapidly leading to higher stove efficiency and therefore good heat recuperation from the stove walls. This observation can be explained by an increase of heat transfer to the stove walls due to the higher turbulence inside the stove when combustion is faster. This behavior indicates that SCG combustion is not suitable for the stove design and may lead to an uncomfortable heating. A recent study showed that masonry stoves are more adapted than cast-iron stoves because it allowed a better heat release and lead to a limitation of the temperature oscillations during the heating periods (Carvalho et al., 2013). One should be reminded that the evaluated stove was designed for conventional wood logs combustion (with respect to the NF Bois de Chauffage standard). In fact, these results are equivalent to those obtained for wood stoves with various wood species (for example, oak and birch). Depending on the wood stove technology (e.g. mass stove), energy recovery may be highly different while combustion efficiency remains in the same order. In our case, the stove performances are very close for different logs. A possible improvement of the exhaust gas composition may be achieved by a modification of the primary air injection system (Prapas et al., 2014).

Conclusion

Spent coffee grounds (SCG), a processing by-product from the coffee industry, was evaluated as a potential feedstock for preparing blended fuel logs for energy production. Hence, an SCG 20 wt%/sawdust 80 wt% blend was transformed into densified logs. Then, the combustion

Table 5
Gas and particle emissions expressed in % for gases and in mg/Nm^3 for particles at 13% O_2 and combustion efficiency of the different biomass logs. Stove power efficiency corresponds to the real heat released of the stove during the combustion test.

Logs	Combustion efficiency (%)	Corrected mean values			Exhaust flow rate (g/s)	Stove power heat (kW)
		$\%CO_2$	%CO	Particles mg/Nm^3		
SCG (20%)/sawdust (80%) log (1.8 kg)	82.25	7.70	0.17	77.1	11.35	13.00
SCG (20%)/sawdust (80%) log (0.9 kg) + beech wood log (0.9 kg)	82.05	9.05	0.15	73.1	9.85	12.57
Beech wood log (2 kg)	81.75	11.20	0.05	50.3	6.77	9.12

Table 6
Results obtained for I and I' indexes (rounded as defined in the "Green Flame" quality label manual) according to Eqs. (8) and (9) for the different combustion tests.

Logs	I index	I' index	Class of performance
SCG (20%)/sawdust (80%) log (1.8 kg)	1 (1.02)	1 (0.98)	★★★★★
SCG (20%)/sawdust (80%) log (0.9 kg) + beech wood log (0.9 kg)	0.9 (0.91)	0.9 (0.90)	★★★★★
Beech wood log (2 kg)	0.3 (0.32)	0.5 (0.48)	★★★★★

performances of three different formulations were tested in a "five star Flamme Verte" labeled stove.

The results show that the combustion tests performed with the different SCG log formulations lead to comparable yields of combustion in comparison with the results obtained with classical wood logs. Nevertheless, CO and particle emissions increase when increasing the rate of SCG, but the exhaust gas emissions and combustion yields always lead to the "five star Green Flame" label achievement, which is essential to sell these densified biofuel logs in the French market. Hence, SCG 20 wt%/sawdust 80 wt% blended logs may be a promising biofuel for energy production in residential applications. However, an improvement of the combustion process is necessary in order to control the energy recovery and dissipation. The stove used in this study was adapted to classical wood logs, and several evolutions must be done to obtain a specific stove dedicated to wood logs or more widely to biofuel logs.

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