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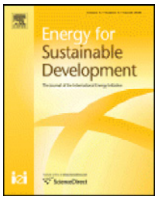

Performance and emissions characteristics of compressed spent coffee ground/wood chip logs in a residential stove

Lionel Limousy [a], Mejdi Jeguirim [a,*], Stephane Labbe [b], Fabien Balay [b], Eric Fossard [c]

[a] Institut de Science des Matériaux de Mulhouse, CNRS, UMR-7361, 15 rue Jean Starcky, 68057 Mulhouse, France
[b] Lorflam Industry, ZA de Kergoussel, 501 route de Caudan, 56850 Caudan, France
[c] RID Solution SAS, La Croix Martin 56460 Lizio, France

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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.

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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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[*] Corresponding author. Tel.: +33 3 89 60 86 61.
E-mail address: mejdi.jeguirim@uha.fr (M. Jeguirim).

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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

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