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EXPERIMENTAL STUDY OF MINIMUM IGNITION TEMPERATURE OF SPENT COFFEE GROUNDS

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Research article

Abstract: The aim of this scientific paper is an analysis of the minimum ignition temperature of dust layer and the minimum ignition temperatures of dust clouds. It could be used to identify the threats in industrial production and civil engineering, on which a layer of combustible dust could occure. Research was performed on spent coffee grounds. Tests were performed according to EN 50281-2-1:2002 Methods for determining the minimum ignition temperatures of dust (Method A). Objective of method A is to determine the minimum temperature at which ignition or decomposition of dust occurs during thermal straining on a hot plate at a constant temperature. The highest minimum smouldering and carbonating temperature of spent coffee grounds for 5 mm high layer was determined at the interval from 280 °C to 310 °C during 600 seconds. Method B is used to determine the minimum ignition temperature of a dust cloud. Minimum ignition temperature of studied dust was determined to 470 °C (air pressure - 50 kPa, sample weight 0.3 g).

Keywords: Coffee grounds, Minimum ignition temperature, Carbonating, Dust layer, Dust cloud.

Introduction

Biomass is expected to be an important source of renewable clean energy in the future due to its CO_2 neutral nature and low sulphur and/or nitrogen content (Mašek, 2008). Biomass can also be combusted directly to produce heat or heat and power simultaneously. However, the efficiency of biomass combustion in conventional stove can reach only 10 - 20 %, depending on feedstock properties (Mai, 2011). In the case of standalone power plants the efficiency for electricity production typically varies around 20 - 30 % (Cohen, 2013).

Coffee is a global favourite interactive beverage prepared from roasted coffee beans, with approximately 500 billion cups consumed every year. Spent coffee grounds, the solid residues obtained from the treatment of coffee powder with hot water to prepare instant coffee, are the main coffee industry residues with a worldwide annual generation of 6 million tons (Yesil, 2013; Tokimoto, 2005). Spent coffee grounds are a residue with fine particle size, high humidity (in the range of 80 - 85 %), organic load and acidity. Spent coffee grounds are rich in sugars polymerized into cellulose and hemicellulose structures. They are composed by a majority of carbohydrates, being mannose (21.2 % w/w), galactose (13.8 % w/w) and arabinose (1.7 % w/w) from hemicellulose, and glucose (8.6 % w/w) from cellulose (Mussatto, 2011).

Usually the spent grounds are used as fuel in the boilers (Silva, 1998). The effect of the admixed inert material on the ignition temperature of a dust layer was studied in the past, for example in the specific cases of coal (Reddy, 1998). Assessing the risk of fire or explosion of an explosive atmosphere in a process where combustible dust is present is based in part on identifying potential ignition sources. The ignition sensitivity of combustible dust can be characterized by measuring the minimum ignition temperatures of a dust cloud or for dust layers and the minimum ignition energy for dust clouds. The minimum ignition temperatures is used to evaluate the probability of ignition by hot surfaces, like a furnace, or moving

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parts being heated by friction, whereas minimum ignition energy provides information on which types of sparks can be considered as ignition sources. If the minimum ignition energy is sufficiently low, electrostatic sparks are likely to ignite a dust cloud (Janès, 2013).

Material and methods

Samples description

Spent coffee grounds are a solid residues with fine particle size, high humidity (in the range of 80 - 85 %), organic load, and acidity, obtained during the treatment of raw coffee powder with hot water or steam for instant coffee preparation (Mussatto, 2011).

According to the standard EN 14774-3 (Solid biofuels.) the spent coffee grounds samples was dried at a temperature of 105 ± 2 °C, until almost zero absolute humidity was achieved (during sieving an increase of samples weight was observed) and consequently by using the sieve machine it was divided into three fractions listed in Tab. 1.

Tab. 1 The sieving fractions percentage of spent coffee grounds

Weight percentage	
Sieve size [μm]	**Coffee grounds [%]**
> 500	38.55
500 - 250	53.90
250 - 100	7.55

The samples were stabilised in a desiccator for 48 hours at 22 °C and at a relative humidity of 30 % before the analysis. The density was determined at approximately 260 kg.m^{-3}. A. Janès and D. Carson (2013) determined the density of coffee waste at around 310 kg.m^{-3} at a relative humidity of 2.6 rel. % and at 83 % grain size larger than 315 μm. This difference may be caused by the different origin and macroscopic properties of the substance.

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) according to standard EN 14775:2009 (Solid biofuels). Ash content was determined on 1.75 %.

A test portion of the general analysis sample is heated out of contact with ambient air at 900 °C ± 10 °C for 7 min. The percentage of volatile matter is calculated from the loss in mass of the test portion after deducting the loss in mass due to moisture according to standard EN 15148:2009 (Solid biofuels). Volatile matter reached the value of 83.48 % (Tab. 2).

Tab. 2 Composition comparison of different samples (dry basis)

Samples	**Volatile matter [%]**	**Ash [%]**	**Fixed carbon [%]**
Upgraded coffee grounds (Mašek, 2008)	-	0.80	-
Spent coffee grounds pellets (Limousy, 2013)	-	1.82	17.46
Spent coffee grounds (Li, 2014)	82.00	1,70	16.30
Nespresso® coffee grounds (Plaza, 2012)	82.90	1.30	-
Spent coffee waste (Pappa, 2012)	84.45	1.00	14.55
Spent coffee grounds (This study)	83.48	1.75	14.72

Determination of the basic elements C, H, N and S was performed on the instrument varioMACROcube from ELEMENTAR. Ultimate analysis was used to control the sulphur content and the potential changes in the structure of the samples. Tab. 3 shows the results of the analysis.

Tab. 3 Ultimate analyses of initial samples (on dry basis)

Sample	**C [%]**	**H [%]**	**O [%]**	**N [%]**	**S [%]**
Upgraded coffee grounds (Mašek, 2008)	54.2	7.3	35.6	2.0	< 0.1
Spent coffee grounds (Silva, 1998)	59.5	7.3	30.7	2.5	-
Spent coffee grounds (Jeguirim, 2014)	61.13	8.99	26.60	2.91	0.37
Spent coffee grounds (Li, 2014)	54.5	7.1	34.2	2.4	0.1
Coffee grounds (Bok, 2012)	54.61	6.59	34.83	3.97	0.00
Spent coffee grounds (This study)	50.77	8.25	38.75	2.16	0.07

Experiment description

To determine minimum ignition temperatures of dust layers (method A) and clouds (method B) a research method was applied, in conformity to the standard EN 50281-2-1:2002.

The method A, has been applied to determine the minimum temperature at which the layer of dust (of specified thickness) located on a heated furnace plate (Fig. 1) undergo thermal decomposition and/or ignite. This method refers especially to industrial equipment with hot surfaces where dust create layers of different thickness which pose danger having contact with air (EN 50281:2002. Electrical apparatus for use in the presence of combustible dust; Polka, 2012). The heater surface should consist of a circular stainless steel plate 200 mm in diameter and not less than 20 mm thick. The plate should be heater by an electrical heating element and its temperature should be controlled by a device for which the sensing element is a thermocouple mounted in the plate at the center and with its junction in contact with the plate and within 1 ± 0.5 mm of the upper surface. The same thermocouple should be connected to a temperature record for recording the temperature of the plate during a test (Classification of Dusts Relative to Electrical Equipment in Class II Hazardous Locations, 1982).

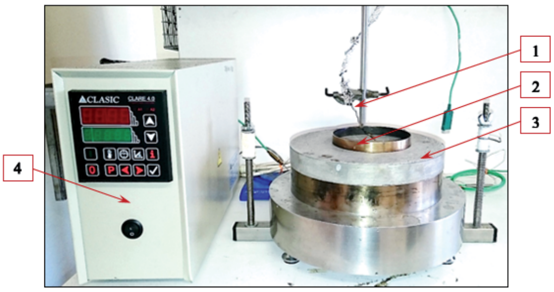

Fig. 1 Main parts of testing device (method A): 1 measurement thermocouple; 2 testing ring; 3 hot plate; 4 control unite

To define minimum ignition temperature of a dust cloud, method B, in which a furnace (Fig. 2) with constant temperature and testing equipment connected to it, was applied. It is used in relation to industrial equipment, inside which dust may exist in the form of short - term cloud. This is a vertical pipe furnace, generally known in literature as the Godbert - Greenwald furnace. The silica tube placed inside the furnace is set up in a vertical position, and its lower end is open to the atmosphere. This pipe is heated until the desired temperature is reached with the use of a device that controls furnace temperature. Below the pipe is a stainless steel mirror which allows visual monitoring of the furnace interior (Polka, 2012).

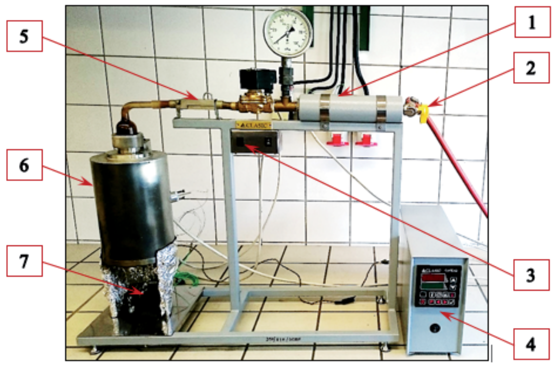

Fig. 2 Main parts of testing device (method B): 1 pressure tank; 2 pressure valve; 3 switch; 4 control unite; 5 dust container; 6 furnace; 7 mirror

Results and discussion

Minimum ignition temperatures of dust layer

The measurements were performed on a samples of spent coffee grounds. Behaviour of the sample during the measurement showed the fact that smouldering and flowing carbonating was visible mainly by the circle edges. The samples were thermally strained by a hot plate. Ring circle improved the conductivity which enables the heat to spread more quickly through the samples. A dust layer strained by the heat carbonated. After volume decrease it was observed that the sample separated from the circle edges. An oxygen from the air was enabled to reach to a larger surface area of the sample and its subsequent initiation. According to the European standard EN 50281-2-1:2002 the chosen sieved size of spent coffee grounds was 250 - 500 μm. The dust layer was 5 mm thick. The background laboratory temperature was 22 °C. Fig. 3 shows smouldering and carbonating of samples in IR spectrum. During testing a thermographic camera was used and subsequently processed by SmartView 3.0 programme. It is obvious that the maximum values of surface temperature were reached on the circumference of the sample. This fact is due to the higher thermal conductivity of the metal hoop, compared with the tested material. The difference between these temperatures decreases during the test, what is a consequence of the overheating of the sample.

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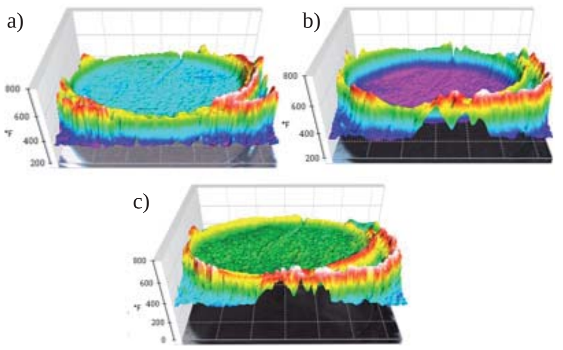

Fig. 3 Visual display of samples in 3D - infrared spectrum: a) 100 s; b) 200 s; c) 300 s

Fig. 4 describes the dependence of the surface temperature of the sample from the time. Samples were isothermally strained for at least 480 seconds, which was sufficient in order to carbonization of the sample. With an increasing temperature of hot plate surface a faster heating of samples with subsequent ignition occurred. This can be explained by faster degradation of the cellulose and lignin. At temperatures higher than 310 °C all of the samples smouldered and carbonized. The temperature of 280 °C was not sufficient to initiate the visible degradation processes of the surface of the sample. This means that the minimum smouldering and carbonating temperature of spent coffee grounds for 5 mm high layer was determined at interval from 280 to 310 °C.

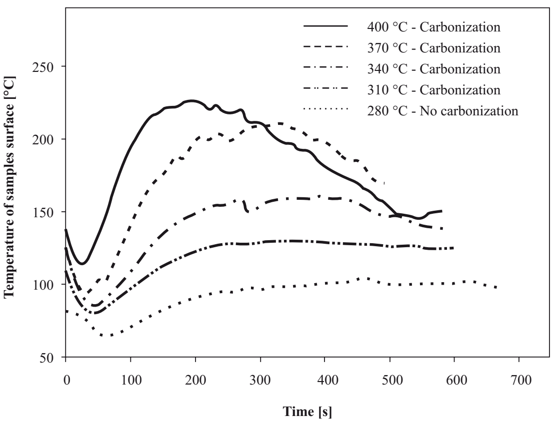

Fig. 4 Temperature dependence of sample surface from the time of exposure to a hot plate

Minimum ignition temperatures of dust cloud

Determination of the minimum ignition temperatures of dust clouds is carried out according to EN 50281-2-1:2002: Methods for determining the minimum ignition temperatures of dust. Method B: Dust clouds in the oven at a constant temperature. For determining the ignition temperature of dust clouds according to the weight of the sample was used a different mass of dust (0.1, 0.2, 0.3, 0.5 g). We also observed the ignition temperature dependence of dust clouds from the pressure of air in combustion chamber (10, 20, 50 kPa).

According to standard EN 50281-2-1:2002 the minimum ignition temperature of studied dust was determined to 470 °C (mentioned EN standard considers the minimum ignition temperature a minimal temperature at which the initiation of samples with the particle size of 100 - 250 μm occurs decreased by 20 °C). Obtained results show that the safety margin of 20 °C required according to STN EN when calculating the minimum ignition temperature of coarse dust (obtained by the sieving machine of nominal mesh size 500 μm) from the data measured for dust particles with a size from 100 to 250 μm is sufficient for the dust from spent coffee grounds. During the experiment, it was found that air pressure affects the initiation temperature significantly. When lower air pressure (10 kPa) was used, the temperature required for ignition of the samples (0.1, 0.2, 0.3, 0.5 g) increased. This was mainly due to insufficient air pressure required for transport of the full dust sample form container to furnace. Low air pressure was not sufficient to spread the dust with subsequent mixing with the air, so were conditions for ignition not created. Using higher air temperatures and pressures a significant part of the sample passed through the furnace in a compact form and without change (no ignition). Using temperatures and pressures just below the flashpoint the individual particles of dust only sparkled without ignition. Construction of the device, specifically the dust container did not allow a complete exhaust of the sample through a silicone tube into the furnace.

Based on the measured data on the ignition temperature of the dust from spent coffee grounds, for the investigated particle sizes, weights of samples and air pressures, was made a prediction on ignition temperatures (within the range studied sample weight and air pressure) by statistical software STATISTICA 10. Prediction was made by the method of least squares (Distance Weighted Least Squares Model). For unambiguous verification of the hypothesis obtained data were submitted by Duncan's test (test was conducted via statistical software STATISTICA 10, at significance level $\alpha = 0.05$).

The ignition temperatures values were obtained by the prediction are shown in Fig. 5. The data demonstrate that particle size and external conditions (the sample weight and the air pressure) have a significant influence on the ignition temperature of dust from spent coffee grounds. Dust layer and dust cloud minimum ignition temperatures of different materials are shown in the tab. 4.

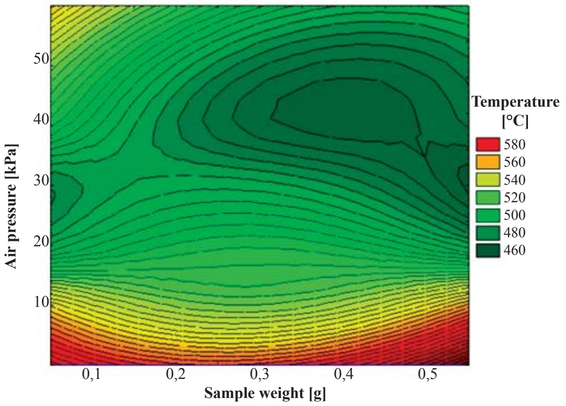

Fig. 5 The effect of sample weight and air pressure on the ignition temperature of dust from spent coffee grounds

Tab. 4 Dust layer and dust cloud minimum ignition temperatures of different materials

Samples	Minimum ignition temperature [°C]	
	Dust layer (5 mm)	Dust cloud
Ground coffee (Janès Agnès, 2013)	290	470
Hop (Polka, 2012)	290	460
Lemon balm (Polka, 2012)	290	480
Buckwheat (Polka, 2012)	320	450
Sunflower hulls (Polka, 2012)	290	460
Coffee (Mills, 2004)	-	410
Coffee (Dustexplosion.info, 2015)	-	470
Non-modified spruce wood		
(Martinka, 2014)	-	430
Spent coffee grounds (This study)	310	470

The pyrolysis products were quantified as follows: noncondensable gases (H_2, CO, CO_2 and C_1 - C_4 hydrocarbons), light tar (mono- and di-aromatics), heavy tar (aromatics heavier than 1-methylnaphthalene), soot that was deposited over the reactor wall and char that was collected downstream of the reactor. The product yields were not influenced by changes in the upgraded coffee grounds feeding rate within the range used (Hayashi, 2000; Hayashi, 2002).

Previous investigations showed that spent coffee grounds contains 40 % lignin, 37 % hemicellulose and 9 % of cellulose (Mussatto, 2011; Tsai, 2012). One may remind that lignin has a lowest O/C atomic ratio close to 0.4 and it is rich in C - C in its aromatic ring as well as methoxyl (–O–CH_3). In contrast, sawdust has a higher O/C atomic ratio due to higher cellulose content. In fact, pine sawdust contains mainly 41 % cellulose, 27 % hemicellulose and 27 % lignin (Saarela, 2005). In fact, it is known that cellulose surface is rich in oxygenated groups. The typical functional groups are hydroxyl (–OH) and ether (C-O-C) (Jeguirim, 2014).

Conclusion

Spent coffee grounds are a by-product of the coffee industry and its processes. This waste product could be potentially used as a basis for the production of agropellets as an energy resource. Therefore, this scientific article studied the fire-technical properties of spent coffee grounds. This methods are used in relation to industrial equipment where dust may exist in the form of short-term clouds. According to EN 50281-2-1:2002 the minimum smouldering and carbonating temperature of spent coffee grounds for 5 mm high layer was determined at the interval from 280 °C to 310 °C during 600 seconds and the minimum ignition temperature of studied dust was determined to 470 °C (air pressure - 50 kPa, sample weight 0.3 g). This study could be used to identify the threats from industrial equipment and constructions, which while working have hot surfaces, on which can be created a layer of combustible dust. The results presented in this study should nevertheless be confirmed by further testing in order to more precisely evaluate the potential risk.

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