Fuel 223 (2018) 451–461

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Ignition sensitivity of solid fuel mixtures

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ARTICLE INFO

Keywords:
Ignition
Co-firing
Solid fuels
Biomass
Waste
Coal

ABSTRACT

Due to both environmental concerns and the depletion of the reserves of fossil fuels, alternative and more environmentally friendly fuels, such as biomass and waste products, are being considered for partial or full fossil fuel replacement. The main disadvantage of these products is their lower energy density compared to fossil fuels. To deal with this several heat and power generation facilities are co-firing fuel mixtures. These processes involve mixtures of flammable dusts whose ignitability and explosibility characteristics are not known and therefore present un-quantified safety risk to the new technologies.

This study reports on these risks and on the reactivity characteristics of two and three components dust mixtures of coal/sewage-sludge/torrefied-wood-pellet. In particular chemical composition, ignition sensitivity parameters (including minimum ignition energy, minimum ignition temperature on a layer, minimum explosive concentration) and flame speed have been determined. In all cases the measured parameters for the mixtures were within the range defined by the lower and upper value of the constituent. However, the expected values do not agree with the experimentally obtained ones, providing more relaxed values than the ones needed on this facilities.

1. Introduction

In 2013, fossil fuels provided 81.2% of the total energy consumed worldwide [1]. For the European Union, this number is slightly smaller and it is decreasing each year, but it still represents a 72.6% of total [1]. Fossil fuels present several disadvantages that are well-known, mainly the environmental problems associated with their use [2] and the depletion of their reserves [3]. Focusing on the future, the European Union members adopted a plan to fight against climate change focusing measurements on emissions cuts, renewables and energy efficiency [4].

Related to this plan, the recovery of energy from biomass and non-recyclable waste products is one of the priorities of the European countries. The “202020 targets” stablish that for year 2020 greenhouse gas emissions should be reduced by 20 percent, renewable energy sources should represent 20 percent of Europe’s final energy consumption and energy efficiency should increase by 20 percent [5].

To achieve these targets, several researches are focused on the study and development of a range of new materials that can be classified as biomass. According to the United Nations Framework Convention on Climate Change [6], the term biomass is defined as:

> *“non-fossilized and biodegradable organic material originating from plant, animals and micro-organisms. This shall also include products, by-products, residues and waste from agriculture, forestry and related industries as well as the non-fossilized and biodegradable organic fractions of industrial and municipal wastes”*

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Materials that have been considered as waste for a long time are nowadays used as new fuels, for example: sewage sludge [7], plastics [8] or organic shells and pits [9,10]. Added to these, traditional solid fuels such as wood have been studied and modified in order to improve their properties. Processes such as pelletization and torrefaction upgrade these materials providing a higher energy density and lowering their handling costs [11,12].

The main problems of these new fuels are that their properties as fuels are not as good as those of coal (that they seek to replace), and that the use of these fuels may require developing new facilities, representing a very high investment.

One of the preferred solutions is the use of co-firing. Co-firing is

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https://doi.org/10.1016/j.fuel.2018.02.106
Received 2 May 2017; Received in revised form 27 December 2017; Accepted 15 February 2018

defined as the combustion of two or more different types of materials at the same time. This technology has been mainly implemented by mixing coal and biomass, and several environmental benefits have been observed such as the reduction of atmospheric emissions of target pollutants compared to traditionally coal-fired power plants [13], and the reduction of particulate matter emissions [14]. Instead of using biomass, co-firing can also take place with waste materials, which not only results in the recovery of energy but also in a substantial reduction of the disposed volume and in the safe destruction of toxic organic residues, solving part of the problem of waste disposal [15–17]. One of the main advantages of co-firing is that the equipment previously used for coal combustion can be used for these mixtures with a much lower economical investment, however, further studies are very much needed to be conducted such as improvement in boilers design, materials and combustion technology [18].

One of the main disadvantages of the addition of these substances to the combustion process is the large amount of moisture they present, which can cause ignition and combustion problems [19]. Decreasing the moisture has positive effects on the flue gas temperature, ignition property, wall heat flux, flame stability and char burnout [20], but they increase the flammability tendency of these mixtures.

With this technology, mixtures of different materials are used in many already existent industrial facilities, but they must be treated as new fuels, as their properties are still unknown. These properties include the energetic properties that are the objective of the mixing process, but also the properties related with their ignition and combustion tendency. Solid dusts present ignition and combustion properties that have to be determined and understood for the design of fire and explosion prevention and protection measures needed in such facilities [21]. Some researchers have studied the flammability behaviour of mixtures of dusts, mainly with an inert dust [22–24]. By mixing any flammable dust with inert dusts, the ignition tendency can be decreased, but the influence that mixing two or more flammable dusts has not been studied yet.

The flammability properties that characterize coal [25], waste [26] and biomass [27] dusts have to be carefully determined in each single case due to their heterogeneity, but mean values show that they present a high ignition risk. This risk will also be present in the mixtures of these materials, and will depend on the proportion of each component in the mixture [24,28].

The main objective of this research was to determine the risk of ignition of coal / waste / biomass mixtures and to what extent this risk may change with the mixture composition make up. To achieve this, the ignition sensitivity of such samples has been studied in this work. The term "ignition sensitivity" involves the parameters related with the ease of ignition and included the Minimum Ignition Temperature on a layer (MITl), Minimum Ignition Energy (MIE) for a dust cloud, and Minimum Explosive Concentration (MEC). These have been determined for a range of mixtures made up with varying the proportions of the component fuels.

2. Materials and methods

2.1. Materials

This study presents the results obtained from the analysis of ten mixtures of coal, thermally dried sewage sludge and torrefied wood pellets in different mass percentages, as shown in Table 1.

Proximate analyses and granulometry of these materials and their mixtures are shown in Tables 2–5. The content of moisture of the three base samples was less than 10%, so they can be defined as dry samples. The three base samples were milled before their use. Coal and thermally dried sewage sludge presented the smaller particle size, having round and hard particles, while torrefied wood pellet particles were elongated and brittle with a larger size.

Table 1
Composition (% by mass) of samples studied.

Sample	Sewage sludge (SS) (%)	Coal (C) (%)	Torrefied wood pellets (TW) (%)
SS	100	0	0
C	0	100	0
TW	0	0	100
NFA-101	25	75	0
NFA-102	50	50	0
NFA-103	75	25	0
NFA-104	0	75	25
NFA-105	0	50	50
NFA-106	0	25	75
NFA-107	75	0	25
NFA-108	50	0	50
NFA-109	25	0	75
NFA-110	33.33	33.33	33.33

2.2. Methods

The chemical and physical characteristics of the ten studied mixtures were determined. Elemental analyses were carried out using a Flash 2000 Thermo Scientific Analyser at the University of Leeds. Proximate and granulometric analyses were performed at the Universidad Politecnica de Madrid. Proximate analyses were performed according to EN 32004 [29], EN 32019 [30] and EN 32002 [31], while granulometry was determined using a Mastersizer 2000 Analyser.

Thermogravimetric and differential scanning calorimetric analyses have been developed to fully describe the thermal susceptibility of the samples in the Universidad Politecnica de Madrid with a Mettler Toledo TG 50. In TG, the weight of the samples is measured as a function of its temperature. The procedure was developed from 30 °C to 800 °C with a heating rate of 5 K/min. Three main parameters are obtained by studying these graphs: initial temperature and the maximum loss of weight temperature for both peaks of the sample. TG with an oxygen stream instead of an air stream was developed, and the oxidation temperatures of the samples were determined in the points where the maximum loss of rate occurred. DSC is used to study the heat exchange of the sample during a heating process. The test was developed from 30 °C to 550 °C, under a heating rate of 20 K/min. In this case, three main parameters are obtained: the temperatures at which the exothermic reaction starts and finishes and the temperature of change of slope, at which the slow exothermic reaction starts to accelerate and become a rapid reaction.

In order to determine the ignition sensitivity of the fuel mixtures, we determined (i) the Minimum Ignition Temperature of a layer (MITl); (ii) the Minimum Ignition Energy of a dust cloud (MIE) and (iii) the Minimum Explosive Concentration (MEC), the pressure rise rate (dP/dt) and the flame speed (Sf).

The Minimum Ignition Temperature of a layer (MITl) was determined at Laboratorio Oficial Madariaga, Universidad Politecnica de Madrid, according to the EN 50281-2-1 [32]. The test equipment consisted of a round metallic surface of 20 mm diameter, electrically heated. It could reach 400 °C and its temperature was controlled with two thermocouples located at the middle point of the plate (Fig. 1). One thinner thermocouple (diameter of 0.20 to 0.25 mm) was located 2 or 3 mm above the surface of the plate, measuring the temperature of the dust layer.

Dust layers were formed with a metallic ring of 100 mm of diameter located in the middle of the plate. Once the target plate temperature was reached, dust was deposited inside the ring with a spatula and distributed. Finally, the layer was levelled and all the excess dust is removed.

It was considered that ignition occurred if (i) Incandescence or visible flame was shown, (ii) a temperature of 450 °C was reached in the middle point of the sample or (iii) a 250 K rise above the set plate