Journal of Loss Prevention in the Process Industries xxx (2014) 1–9

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Explosion reactivity characterisation of pulverised torrefied spruce wood

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ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form
7 December 2014
Accepted 14 December 2014
Available online xxx

Keywords:
Dust explosion
Biomass
Torrefaction
Reactivity
Combustion

ABSTRACT

Pulverised biomass is increasingly being used for power generation in 100% biomass plants or mixed with coal as a way of reducing greenhouse gas emissions. The fire and explosion hazards of pulverised wood and other agricultural waste materials have been recognised for some time. However, safety data for biomass are very scarce in the public literature, and non-existent for upgraded biomass products such as torrefied biomass. This is largely due to the challenges that biomass poses for explosion characterisation in the standard methods (1 m^3 ISO vessel or 20 L sphere). The authors have developed and calibrated a new system for the 1 m^3 ISO vessel that overcomes these challenges. In this work we present the first data in the open literature for the explosion characteristics of torrefied biomass. Results for untreated Norway spruce wood and Kellingley coal are also included for comparison. Flame speeds and post-explosion residue analysis results are also presented. Torrefied spruce wood was found to be more reactive than Kellingley coal and slightly more reactive than its parent material in terms of K_{St}, P_{max} and flame speed. The differences between coal and biomass samples highlight that it should not be assumed that safety systems for coal can be applied to torrefied or raw wood materials without suitable modifications.

1. Introduction

Pulverised biomass (on its own or co-fired), accounted for nearly 14% of the total renewable electricity generation in the UK in 2012. The total contribution of renewable energy to all energy consumption in the UK was 3.8% in 2011. This comprised 8.7% of electricity, 2.2% of heat and 2.9% of transport fuel coming from renewable sources (DECC, 2013). The UK has agreed to the EU wide renewable energy target of 20% of all energy to come from renewables by 2020, in line with the EU 2009 Renewable Energy Directive (European Parliament, 2009). The UK's specific target is to achieve 15% of all energy from renewables. The UK's Department of Energy and Climate Change (DECC) has announced that the UK will attempt to meet this target with 30% renewable electricity, 12% renewable heat and 10% renewable transport fuel (Davey et al., 2011). As a result of the government's plans, the use of biomass for generation of power, heat and transport fuels is forecasted to double or quadruple 2011's levels by 2020 (from 12 TWh to 30–50 TWh) (Davey et al., 2011). Economic incentives are in place such as the renewable obligation certificates to achieve this. However, in power generation, there are challenges mainly related to retrofitting plants in order to use biomass, a material with different characteristics to fossil fuels that affect the general operation of plants: efficiency, storage, handling, etc.

Biomass properties can be upgraded through torrefaction. This is a thermal pre-treatment in which biomass is subjected to temperatures of around 300 °C in an inert atmosphere for a certain period of time. The end product is more energy dense, hydrophobic and easy to grind with properties similar to low rank coals. Torrefaction of biomass decreases the transportation and storage costs and also enables co-milling with coal or for coal mills to be used with 100% torrefied biomass, which is attractive in the current scenario where authorities are encouraging coal plants to co-fire or to convert to 100% biomass plants rather than building new 100% biomass plants.

The implicit assumption in replacing coal with biomass is that biomass behaves in a similar way to coal and therefore the present

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http://dx.doi.org/10.1016/j.jlp.2014.12.009
0950-4230/

combustion and safety (fire and explosion) systems are adequate. The scarcity of explosibility data on biomass and the absence of any data for torrefied biomass prevent the informed assessment of suitability of the existing safety systems. The frequency of fire and explosion incidents in such plants (Butcher, 2011; Holland, 2011; Renewables International Magazine, 2011) would suggest specific combustibility and explosibility data are required for biomass and treated biomass powders.

1.1. Biomass explosion characterisation challenges

Pulverised biomass and torrefied biomass present a few characteristics which pose challenges to the standard methods for determining explosion characteristics using the 1 m^3 ISO vessel or the 20 L sphere (British Standards Institution, 2006). Wood biomass and some torrefied biomass materials can present very low bulk densities (ca. 200–300 kg/m^3), therefore the standard dust holders cannot hold enough dust for a complete characterisation of the samples. The addition of another 5 L volume dust holder used in parallel with the standard dust holder is required for low bulk density dusts in the standard, and this requires new calibration procedures if the same K_{St} values are to be achieved. In addition, the fibrous nature of most biomass dusts prevents a correct dispersion of dust from the external dust holder into the explosion vessel, with the standard injection system blocking with biomass and no biomass flows into the explosion chamber.

The flammability and reactivity of biomass and other low bulk density and fibrous dusts has been the object of study of many researchers. Early studies exist on the explosibility of non-traditional dusts using the Hartmann tube/bomb (Jacobson et al., 1961; Nagy et al., 1965; Eckhoff, 1977), however this method of explosion characterisation was abandoned due to bad dust dispersion amongst other issues (Makris and Lee, 1989). Using the current explosion characterisation methods (1 m^3 or 20 L sphere vessels), (Bartknecht, 1989) extended the dust holder volume and proposed a longer ignition delay for the new system, however, the most reactive mixtures were not comparable to the standard. Marmo (2010) studied the explosibility of textile fibres with a 20 L sphere using the rebound nozzle, however, there was no reference to dispersion problems. Wilén et al. (1999) worked with fibrous biomass samples, different dispersion systems were tested and calibrated to give the same K_{St} values as the standard system, however, the reproducibility of other parameters was not proven. Amyotte et al. (2012) investigated the explosion characteristics of fibrous wood and polyethylene dusts of different particle size. At high concentrations and larger particle size part of the dust was placed directly inside the 20 L sphere fitted with a rebound nozzle. This practice (also used by Iarossi et al. (2012)), with polyamide and polyester fibres) was likely to result in variability of dust dispersion patterns, and the results from Amyotte et al. (2012) showed that the maximum explosion pressure for wood samples was indeed variable. The variability in K_{St} was not discussed but it was likely to be larger, as the rate of pressure rise is typically more sensitive to dissimilar dispersion patterns. Garcia-Torrent et al. (1998), Conde Lazaro and Garcia Torrent (2000) used extended 25 L dust holders for high dust loadings for hyperbaric explosion tests with biomass. They modified the ignition delay and dispersion pressure and in turn concluded that the results obtained were not comparable to the standard system due to varied turbulence levels. Dyduch and Pekalski (2013) obtained promising results using statistical methods for the measurement of explosion parameters. These improved the accuracy of measured explosion characteristics and could allow measurements of K_{St} and P_{max} of difficult dusts.

A further challenge in the explosion characterisation standard methods (also not specific to biomass powders only) is that after each test, residual masses of dust are found in the dust holder and in the explosion chamber (Pilão et al., 2006; Sattar et al., 2012a, 2012b). The remaining dust in the external holder does not take part in the explosion and therefore it should be taken into account and the concentration that actually participated in the explosions should be used. Most researchers and testing labs do not report or account for the non-injected powder. A further problem is the practice of reporting dust concentrations as gm^{-3} and not as equivalence ratio which is a much more informative parameter. Expressing concentrations as equivalence ratios shows that most reactive mixtures of dusts are extremely rich, as opposed to the most reactive mixtures of gases, always found for mixtures slightly richer than the stoichiometric mixture. In many cases the elemental analysis of the dust is not given so it is impossible to know the stoichiometric concentration. Consequently explosions safety parameters are rarely linked to fundamental combustion parameters, the most important of which is to know where the flame reaction zone is relative to stoichiometric. In spite of the importance of the explosion flame speed, from which the burning velocity can be calculated, no such measurements of reactivity are made for pulverised dust, which makes any modelling of dust explosion protection impossible. The current rate of pressure rise reactivity data is entirely empirical. Flame speed data and flame front equivalence ratios are determined in the present work as well as the conventional empirical parameters.

A great challenge is also posed by the dust found inside the vessel after the explosion, since it is often a mixture of partially burnt and unburnt particles. Therefore, it is unclear whether this dust participated in the main combustion reaction. Previous work was carried out by the authors to investigate this matter (Sattar et al., 2012a, 2012b), otherwise this issue has rarely been acknowledged in the literature and the focus was only to investigate the difference in particle morphology before and after an explosion (Hertzberg et al., 1982; Wilén et al., 1999; Pilão et al., 2006). Furthermore, an accurate measurement of minimum explosion concentrations (MEC) is unlikely with the standard methods, since it is difficult to accurately know the concentration that took part in the combustion. Previous work by the authors addressed this issue and new techniques have been explored in order to provide an accurate measurement of MEC (Huéscar Medina et al., 2013).

1.2. Reactivity of biomass and torrefied biomass

The work published on biomass explosibility in the literature is inconsistent with respect to the reactivity of biomass relative to coal (Wilén et al., 1999). For torrefied biomass the reactivity of samples has been investigated through low heating rate techniques such as thermogravimetric analysis and subsequent derivation of devolatilisation kinetics. These results have shown that torrefied materials would present higher activation energies (E_a) which increased with torrefaction severity (higher temperature and longer residence times) (Darvell et al., 2010; Broström et al., 2012). Torrefaction decreases the moisture and volatile content and increases the ash content, thus, the loss of volatiles and the presence of more ash could reduce the reactivity of torrefied materials at the same time that less moisture content could increase it. Particle size could also affect the relative reactivity of torrefied biomass since torrefied biomass becomes more brittle with increased torrefaction severity and therefore when a raw biomass and a torrefied biomass are pulverised through the same procedure, torrefied material is bound to have a higher proportion of fines than the raw parent material. Previous work by the authors (Huéscar Medina et al., 2013) showed that MEC of torrefied samples occurred at lower equivalence ratios (Ø~0.2) than for coal (Ø~0.5) which indicates higher reactivity of torrefied materials in comparison to coal.

Please cite this article in press as: Huéscar Medina, C., et al., Explosion reactivity characterisation of pulverised torrefied spruce wood, Journal of Loss Prevention in the Process Industries (2014), http://dx.doi.org/10.1016/j.jlp.2014.12.009