Fuel Processing Technology 157 (2017) 1–11

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Research article

Characterising pulverised fuel ignition in a visual drop tube furnace by use of a high-speed imaging technique

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ARTICLE INFO

Article history:
Received 13 August 2016
Received in revised form 1 November 2016
Accepted 4 November 2016
Available online 16 November 2016

Keywords:
Pulverised fuel particle
Ignition distance
Combustion image analysis
Visual drop tube furnace
Biomass co-firing with coal

ABSTRACT

This study investigates the ignition characteristics of pulverised coal, biomass and co-firing by use of a visual drop tube furnace (VDTF) and a high speed imaging technique. Three coals (anthracite, a bituminous coal and a lignite), four biomasses (Pine, Eucalyptus, Olive Residue and Miscanthus) and various biomass-coal mixtures were tested. With each coal, biomass or their mixture, a distinct flame was established within the VDTF through the continuous feeding of the fuel under the environment of air and at a furnace temperature of 800 °C. To observe the ignition point, a Phantom v12.1 high-speed camera was used to capture the videos of fuel combustion at 500 frames per second (FPS). A technique was developed using MATLAB's image analysis tool to automate the ignition point detection. The results of the image processing were used to statistically analyse and determine the changes to the ignition behaviour with different fuels and co-firing ratios.

The results obtained with the tested coals have shown that the distance to ignition increases as the coal volatile matter content decreases, whereas the opposite trend was found for the biomass fuels. Further, the addition of biomass to the anthracite significantly reduces the distance to ignition but a much less pronounced effect on the ignition was found when biomass was co-fired with the bituminous coal or lignite. The synergistic effect on the ignition of biomass-anthracite mixture is mainly attributed to the high volatile content and the potential effects of catalysis from the alkali metals present in the biomass. The results of this study have shown that the VDTF testing coupled with the image analysis technique allows for an effective and simple method of characterising ignition behaviours of pulverised coal, biomass and their mixtures.

1. Introduction

Visualising combustion using imaging techniques is a simple non-intrusive method that can reveal combustion characteristics of individual pulverised fuel (PF) particles and PF burner flames [1,2]. This is usually realised by recording the combustion events occurring in a transparent furnace or through the transparent observation windows of a non-transparent furnace using a high frame rate video camera [2,3,4]. Post-processing and statistically analysing the captured images can determine the ignition behaviours of pulverised fuel particles, flame size, shape and stability. The use of transparent furnaces to observe particle ignition/combustion is not new as there are a number of previous publications in this field [1–3,5], however, image capture is not limited to this type of set-up as imaging techniques encompass a variety of applications - from laboratory scale single particle tests [6], to plant-scale flame observation [4,7–9]. Levendis et al. [2] used high speed imaging techniques to observe single particle combustion for coal and sugarcane-bagasse using a drop tube furnace with a viewing window. Their results specifically demonstrated the technical feasibility of high speed video capture in a combustion environment. A similar study by Zhang et al. [3] focused on measuring the change in combusting particle velocity as it travelled through the furnace. As with the study of Levendis et al. [2], a standing flame was not generated in the test conditions of Zhang et al. [3]. González-Cencerrado et al. [9] successfully used high-speed imaging to characterise the flame behaviours of a 500 kW_{th} swirl burner co-firing coal and biomass in terms of flame brightness, fluctuation amplitude, distribution symmetry, and oscillation frequency. Matthes et al. [4] demonstrated the on-line measurement capability of a high-speed camera set-up in a standing flame environment with a 1 MW_{th} multi-fuel swirl burner. Molcan et al. [8] characterised biomass and coal combustion using a 3 MW_{th} test facility equipped with a low-NOx burner. An optical probe was positioned adjacent to the low-NOx burner to measure the flame temperature profile using two-colour pyrometry. Although a standing flame was observed in [4,8,9], the relative magnitude of the set-up incurred significant testing time and cost. Thus, it would greatly reduce cost and save time if the study on the flame/combustion behaviours of PF fuels, whether coal, biomass or their mixtures, is carried out with a laboratory-scale furnace that can produce a propagating flame without the use of a burner. In addition, literature

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http://dx.doi.org/10.1016/j.fuproc.2016.11.002

survey has confirmed that high-speed imaging techniques have rarely been applied to the study of a distinct flame established through the continuous fuel feed without the use of a burner on a laboratory scale furnace such as a drop tube furnace which has been widely used for the ignition studies of PF particles [1,2,5]. A study by Levendis et al. [10] in 1998 already demonstrated the feasibility of such a set-up to observe combustion using high-speed cinematography.

Co-firing has become increasingly prevalent in power plants as a means to introduce biomass into the fuel mix, and plant operators can receive financial subsidies for doing so, without the higher capital investment of undertaking a full conversion to burn biomass exclusively. In being able to predict the ignition of fuel blends, plant operators could envisage the risks of mill fires when the fuels are co-milled, and on flame stability and potential ‘blow-back’ for safe boiler operation [7,11]. A study by van de Kamp and Morgan [12] highlighted the trade-offs that needed to be considered when choosing a co-firing fuel and the mixture ratio with coal. Although the study was carried out in 1990′s, the core issues identified such as grindability, slagging, fouling and emission trade-offs are still relevant to the current co-firing practices in power plants. Based on the findings in literature [13], it was hypothesised that the distance to ignition, or stand-off distance, would not correlate directly to the proportion of each fuel that was mixed, in so-called ‘additive’ behaviour. Rather, a more complex synergistic interaction would occur where, for example, a small addition of biomass to coal would cause a disproportionately large reduction in distance to ignition.

Predicting the ignition behaviour of co-firing fuels is not simple, as has been found with investigations on the combustion and ignition of blended coals [7,8,14]. Coals with the same proximate analysis may not necessarily have the same ignition and flame stability characteristics because the ignition depends on early heat release and not on early volatile release [7]. Co-firing on the other hand can result in a shift of the ignition and burnout to lower temperature regions due to the rapid evolution of volatiles from biomass [15]. Moon et al. [15] found that an addition of 10% biomass (blending ratio based on weight) to a low-rank sub-bituminous coal resulted in a significantly enhanced ignition reactivity of the low rank coal. Therefore, the change in the ignition behaviour when blending biomass and coal can be related to two possible causes: either the change is due to the biomass volatile release and ignition triggering the coal to ignite at a lower temperature [15], and/or by relating to the role of alkali metals in the biomass ash, which can catalyse the combustion process [16].

This paper describes how the Visual Drop Tube Furnace (VDTF) was utilised to characterise the ignition and combustion behaviours of biomass and coal, both individually and in various ‘co-firing’ combinations. Experiments were conducted using the VDTF system that has two water-cooled probes used for continuous feeding and collection of fuel and ash respectively. Although the quartz glass furnace can only be heated to a maximum temperature of 1050 °C, it allowed for the visual observation of the combustion process through a long quartz viewing window. The captured high-speed videos were post-processed frame-by-frame using MATLAB's image analysis tools to statistically describe ignition point fluctuation. To the best of our knowledge, this particular method of automating ignition point analysis has not been reported in literature, especially in the context of solid fuel combustion flames established by continuous fuel feeding, rather than by a burner, in a laboratory-scale combustion furnace such as a drop tube furnace.

2. Methodology

2.1. Apparatus

2.1.1. Visual drop tube furnace

To observe the particle combustion processes, a Visual Drop Tube Furnace (VDTF) was specially designed and manufactured. The VDTF is a vertically oriented laminar flow reactor consisting of a transparent quartz work tube that has a 50 mm internal diameter, a 5 mm thick wall, and is surrounded by heating elements throughout its heated length (1000 mm) (see Fig. 1 for the photographs of the VDTF setup and Fig. 2 for the VDTF schematic). A long viewing window (560 mm × 30 mm) is located parallel to the work tube orientation and is positioned at the mid-section of the furnace assembly. Pulverised fuel particles were continuously injected at a mass flow rate of 1.2 g/min through a water-cooled feeder probe using air as a carrier gas at 1 L/min. The collector probe was also water cooled to quench the fuel particles after passing the ‘hot combustion’ zone. Secondary air at 5 L/min was introduced at the top of the furnace, co-axially with the primary air from the gap between the inner wall of the work tube and the external wall of the feeder probe. In addition, the flowrate setting for the vacuum pump was matched to the total inlet gas flow. This flow set-up results in a low Reynolds number throughout the length of the work tube. The laminar flow condition ensures that pulverised fuel particles are entrained by the gas flow and travel in a narrow stream along the centre axis of the

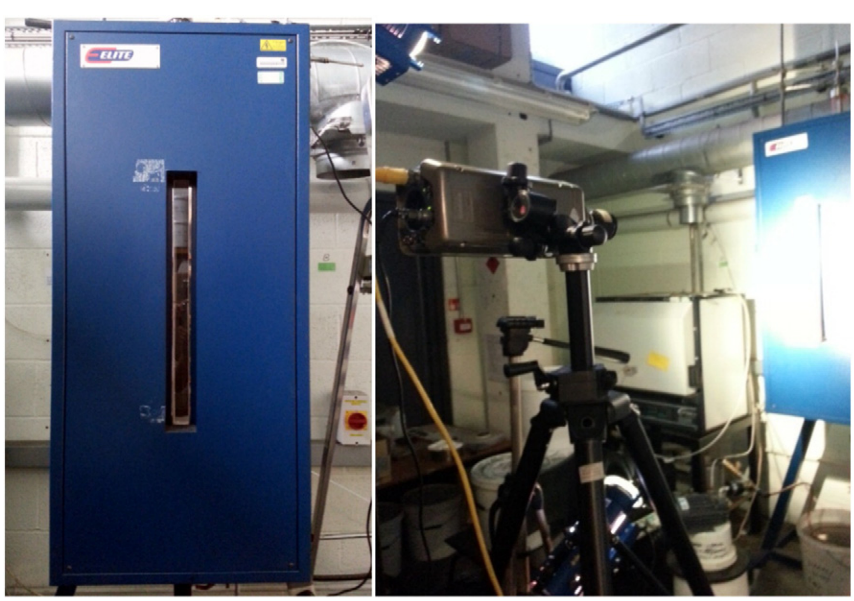

Fig. 1. Visual Drop Tube Furnace with a long viewing window (left) and video capture set-up showing Phantom V12.1 high speed camera with 105 mm Nikon lens (right).