Fuel 89 (2010) 26–35

Contents lists available at ScienceDirect

Fuel

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

Experimental analysis of the ignition front propagation of several biomass fuels in a fixed-bed combustor

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ARTICLE INFO

Article history:
Received 9 December 2008
Received in revised form 16 January 2009
Accepted 25 January 2009
Available online 14 February 2009

Keywords:
Biomass fuel
Fixed-bed combustion
Ignition front propagation

ABSTRACT

Fixed-bed combustion in a tube reactor is a useful procedure to exploit a large variety of biomasses obtaining accurate in-bed data. In this paper, the ignition front propagation velocity is experimentally studied in a counter-current process for eight different biomass fuels with a wide range of origins, compositions and packing properties. Air mass flow rate is the main operative parameter and clearly distinguishes three stages of combustion (oxygen-limited, fuel limited and cooling by convection). The impact of the excess air ratio is also analyzed. This parameter confirmed that the maximum front velocity is achieved under sub-stoichiometric conditions, where the cooling effects of excessive air are minimized. Other variables with a major influence on the ignition front velocity are moisture and ash content. Finally, an uncertainty analysis is included to determine the accuracy of the entire measurement process.

1. Introduction

The use of biomass in the field of energy generation is one of the mainstays of sustainable development. Nowadays, considerable effort is being put into research in this area in order to enhance the usefulness of these fuels. Pelletization is one of the best treatments for adapting available biomass [1–3]. This process reduces transport and handling problems and also improves the homogeneity, volumetric calorific value and feeding automation of the fuel. Nevertheless, from the perspective of economic viability, the suitability of other untreated biomass fuels from secondary sources (agricultural activities, wastes...) also needs to be assessed.

Another important issue regarding the use of biomass involves the dispersed origin of these feedstocks. As biomass is not a centralized resource; its exploitation in small-scale combustion plants is effective because the logistics costs are reduced. Accordingly, combustion based on fixed-bed is probably the more attractive solution to adopt, mainly due to its relative simplicity and low commissioning and running costs. Therefore, this technology is fairly widespread in the household sector, which accounts for over 20% of the total fuel consumption in the EU [4] and is of capital interest for biomass application in the medium term. Regarding the feeding technology, introducing fuel from the top, especially in small-scale systems, has been associated with bed perturbation, thereby promoting a peak in emissions [5]. Thus, modern combustion systems generally avoid dropping the fuel onto the bed by feeding fuel from the bottom or from one side of the bed.

Modelling may help to increase our understanding of the combustion processes taking place in the combustor. To achieve a suitable model, several combustion parameters must be fixed. Since it is difficult, or even impossible, to obtain accurate in-bed data from a full-scale fixed-bed combustor, this task becomes easier using a simple geometry test-rig with one-dimensional behaviour. Thus, the study of the ignition front velocity (mass and heat release rate) in a tube combustor will have several benefits. It is also assumed that with certain simplifications the use of the model could be extrapolated to more complex systems and probably to fixed and moving-beds, which present a certain similarity with fixed-beds [6,7].

Taking into account all these premises, an experimental analysis of the ignition front propagation of several biomasses in a mainly one-dimensional fixed-bed combustor will be considered in this paper. Untreated and pelletized fuels will be burnt and a large amount of data will be obtained to provide a better understanding of the process and allow us to create a combustion model in future work.

2. Experimental

2.1. Experimental rig

A fixed-bed combustor was constructed specifically for this work. The solid particles of fuel are randomly packed in a tube forming the bed. The system comprises two structures: the base, or plenum, and the tube combustor (Fig. 1). The plenum, made of carbon steel with a circular cross-section reduces the turbulence of the inlet air before entering the combustor, so a flat velocity

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doi:10.1016/j.fuel.2009.01.024

Nomenclature

k	shape factor of the Rosin–Rammler distribution (–)
l	mean particle length (mm)
LHV	lower heating value in water basis with ash (as received) (kJ kg^{-1})
M	mass (kg)
m''_{AIR}	air flow rate (kg m^{-2} s^{-1})
m''_{IG}	ignition mass flux (kg m^{-2} s^{-1})
M	accumulated mass
M_T	total mass of the distribution
n	excess air ratio (referred to stoichiometric air) (–)
N	number of elements
r_{eq}	radius of the equivalent sphere (mm)
S_a	stoichiometric air (kg of dry air per kg of fuel burnt)
S_P	surface of the particle (m^2)
t	time (s)
$\dot{T}''_f$	thermal flow (kW m^{-2})
r	result
v	velocity (m s^{-1})
$v_{IG\ max}$	maximum linear velocity of the ignition front
V_P	volume of the particle (m^3)
x	distance between two adjacent thermocouples (m)
z	variable
Δt	time difference between two adjacent thermocouples (s)

Greek letters

δ	uncertainty
ε	porosity of the bed (–)
λ	characteristic length of the distribution (mm)
ρ	bulk density (kg m^{-3})
ρ_P	density of the particle (kg m^{-3})
σ_T	total uncertainty
σ_N	systematic uncertainty
σ_S	statistical uncertainty
ψ	sphericity (–)

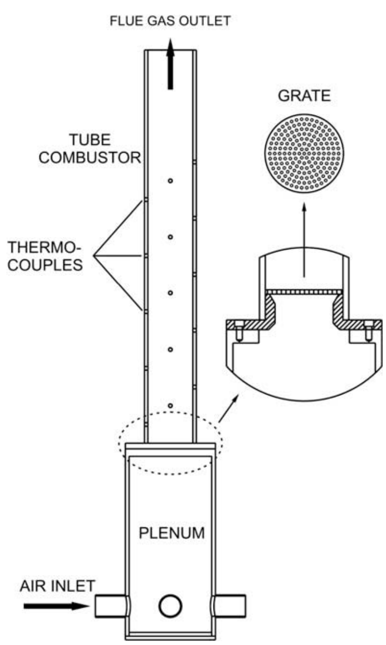

Fig. 1. Scheme of the fixed-bed combustor.

front generation prior to the grate could be assumed. Four different air inlets are available if required to enhance air distribution. Two different tubes are available for the test. They are connected to the plenum with a flange over which the grate is placed, and they have a circular cross-section with an inner diameter of 130 mm and a height of 1050 mm. The burner used for the ordinary tests is made of 7 mm thick carbon steel. The other is made of 7 mm thick transparent Borosilicate, which allows for the visual inspection of certain selected tests, providing useful information and knowledge about the behaviour of the system. The grate is a perforated plate of 3 mm thick carbon steel with circular holes of 6 mm diameter representing a 35% open area.

For measuring the bed temperatures at different levels, 12 K-type thermocouples (Ni–Cr) are radially placed every 50 mm in the duct but their tips are always on the axis of the tube. The air is supplied by a fan controlled by a variable frequency drive to provide a constant flow rate as the pressure drop diminishes due to fuel consumption. The air mass flow rate is measured by a mass flow meter.

Regarding the fuel bed mode, the system is a batch reactor, which implies unsteady conditions. However, the process can be assumed as quasi-steady because the rate of change of its variables in the range of interest is assumed to be slow compared with the response rate of the measurement system [8]. Therefore, once the ignition front is formed, it advances almost steadily and the movement of the ignition front is similar to that of an under-bed system with continuous feed (steady). The air direction is updraft, while the solid phase (fuel) does not move. However, a counter-current configuration could be considered attending to the relative movement between the air flow and the ignition front propagation [9], as can be seen in Fig. 2. As opposed to the co-current mode, dominated by convective heat flow, in the counter-current mode the radiative and diffusive heat flow makes the front move against the air flow while the convective heat flow withholds the propagation of the conversion front. The authors also recommend viewing the pictures and videos in the electronic Annex 1 to the online version of this article, as it provides useful information about the process.

2.2. Ignition front propagation

The test starts at the bed top layer, ignited by a pre-heating device. After only a few minutes, the velocity of the ignition front stabilizes and the system can be treated as a reacting wave in an infinite medium [10]. Once fully developed, the conversion front is as shown in Fig. 2. The upper part of the solid phase is occupied by the char particles that are being oxidized by the air crossing the bed. The devolatilization layer is placed beneath the char layer, which supplies heat by radiation and conduction. The gases leaving this area are entrained by the air travelling through the char layer to be finally burned in the gas phase detached from the packed bed generating the flame. In the lower part of the conversion front, the fuel is being preheated and dried by the heat conducted from the upper layers. During the process, ash and char particles become light and some of them are expelled by the air and leave the bed and also the system. This phenomenon, known as elutriation, avoids the formation of a thick ash layer in the top surface which could shield the bed from the radiation of the flame, cooling the bed [9].

This opposite airflow and flame propagation as modelled in several references [10–17] promotes the appearance of the three reac-