Fuel Processing Technology 120 (2014) 22–33

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Biomass co-firing under oxy-fuel conditions: A computational fluid dynamics modelling study and experimental validation

L. Álvarez [a], C. Yin [b], J. Riaza [a], C. Pevida [a], J.J. Pis [a], F. Rubiera [a],*

[a] Instituto Nacional del Carbón, INCAR-CSIC, Apartado 73, 33080 Oviedo, Spain
[b] Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark

ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form 29 November 2013
Accepted 1 December 2013
Available online 22 December 2013

Keywords:
Biomass co-firing
Synergy effects
CO_2 capture
Oxy-fuel combustion
Below-zero CO_2 emissions
CFD

ABSTRACT

This paper presents an experimental and numerical study on co-firing olive waste (0, 10%, 20% on mass basis) with two coals in an entrained flow reactor under three oxy-fuel conditions ($21\%O_2/79\%CO_2$, $30\%O_2/70\%CO_2$ and $35\%O_2/65\%CO_2$) and air–fuel condition. Co-firing biomass with coal was found to have favourable synergy effects in all the cases: it significantly improves the burnout and remarkably lowers NO_x emissions. The reduced peak temperatures during co-firing can also help to mitigate deposition formation in real furnaces. Co-firing CO_2-neutral biomass with coals under oxy-fuel conditions can achieve a below-zero CO_2 emission if the released CO_2 is captured and sequestered. The model-predicted burnout and gaseous emissions were compared against the experimental results. A very good agreement was observed, the differences in a range of ±5–10% of the experimental values, which indicates the model can be used to aid in design and optimization of large-scale biomass co-firing under oxy-fuel conditions.

1. Introduction

The combustion of coal in power plants generates a large amount of CO_2 which is one of the major contributors to global climate change. A diverse power generation portfolio including Carbon Capture and Storage (CCS) technologies and renewable energies is needed to reduce current atmospheric CO_2 concentration of 393 ppm to below 354 ppm in 1990. During oxy-coal combustion, coal is burnt in a mixture of oxygen and recycled flue gas (mainly CO_2 and H_2O), to yield a rich stream of CO_2 which, after purification and compression, is ready for sequestration [1]. Co-firing biomass with fossil fuels in existing utility boilers is also a feasible technology which can not only significantly reduce CO_2 emissions but also increase the share of renewable energy sources in energy systems [2,3]. The combination of oxy-coal combustion with biomass co-firing could afford a way to increase CO_2 capture efficiency [4]. Biomass co-firing has been successfully performed in over 200 installations worldwide for a large number of combinations of fuels, either in pilot tests or as part of commercial enterprises [5]. Though problems may arise in relation to biomass transport costs and difficulties in milling, these can be manageable if adequate consideration is given to the fuels, design and operating conditions used in the burners and boilers [6].

Compared with biomass co-firing, oxy-fuel combustion is still in the demonstration stage, with plans for industrial scale-up to come into effect in the near future [4]. The successful implementation of oxy-fuel combustion depends on fully understanding the difficulties that can arise from replacing nitrogen by CO_2 in the oxidizer stream. Oxy-fuel conditions strongly promote radiative heat transfer, as a result of the much higher levels of CO_2, H_2O, and in-flame soot, as well as the different CO_2/H_2O ratio to that of air-firing combustion [7]. Other aspects of combustion, such as volatile combustion, flame ignition and stability, or pollutant formation, may also be affected [8]. Biomass co-firing under oxy-fuel is likely to bring up more uncertainties. Biomass co-firing under oxy-fuel conditions is an attractive option to simultaneously increase the use of renewable energy sources, exploit the favourable synergy effects of biomass/coal co-firing and achieve below-zero CO_2 emissions, which has been very little investigated so far [9–12]. For instance Smart et al. [11] evaluated the impact of co-firing biomass on pollutant formation, burnout and heat transfer under oxy-fuel conditions in a 0.5 MWt combustion test facility. Experiments at laboratory scale have been focused on the effects of different co-firing ratios on burnout and NO emissions [12].

Computational Fluid Dynamics (CFD) models have been used to simulate pulverised coal and biomass co-firing in conventional combustion systems [13–15]. In recent years, on the basis of the accumulated knowledge of the fundamental differences between air-fuel and oxy-fuel combustion, much effort has been devoted to developing and validating sub-models for the new combustion environment. For instance, new approaches have been developed for heat transfer modelling in environments with high concentrations of CO_2 and H_2O vapour, e.g., the Weighted-Sum-of-Gray-Gases-Model (WSGGM) refined for oxy-fuel combustion modelling [16,17]. Specific models for volatile combustion in CO_2–rich environments [18] and for char

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* Corresponding author. Tel.: +34 985 119090.
E-mail address: frubiera@incar.csic.es (F. Rubiera).

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http://dx.doi.org/10.1016/j.fuproc.2013.12.005

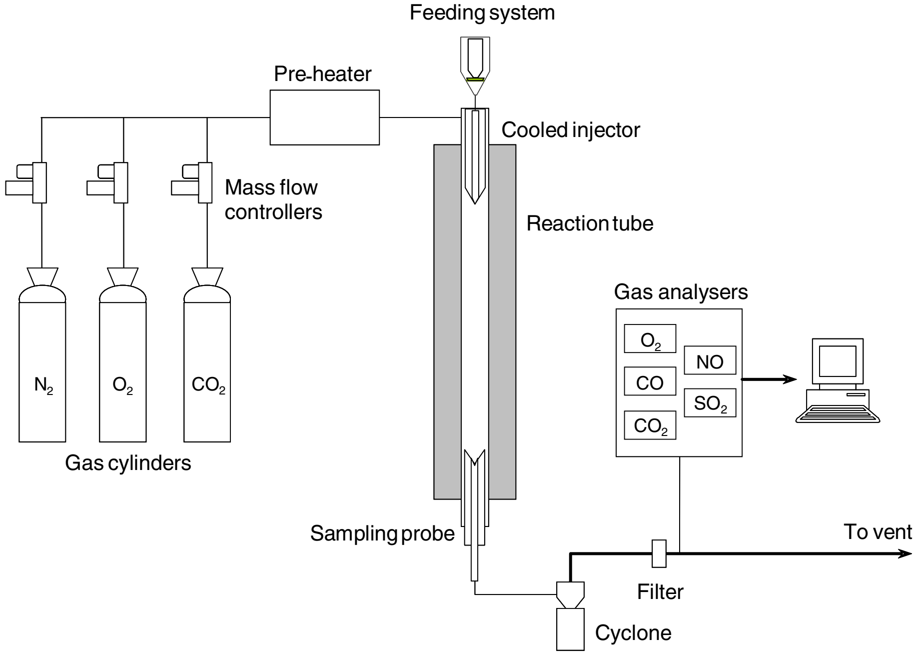

Fig. 1. Schematic diagram of the entrained flow reactor (EFR).

combustion under oxy-fuel conditions [19] have also been developed. In terms of modelling of biomass co-firing under oxy-fuel conditions, a recent paper by Holtmeyer at al. [20] could be the only effort in literature, in which the effect of co-firing sawdust and a subbituminous coal on NO emissions in air and oxy-fuel conditions was studied.

The main objective of this paper is to comprehensively study co-firing biomass with coals under air-fuel and oxy-fuel conditions in a lab-scale entrained flow reactor (EFR). The computational fluid dynamics (CFD) study is the main workhorse and the experimental study is used to validate the CFD modelling. Among others, the effects of biomass shares in co-firing (from 0 to 20 wt.% of biomass), firing conditions, and different coals to be separately used in co-firing on the overall combustion behaviour and NO emissions are investigated and discussed.

2. Experimental setup

All the combustion experiments of this study were performed in a down-fired EFR, which has been introduced in detail in Riaza et al. [21]. Fig. 1 shows a schematic diagram of the reactor. The EFR has an internal diameter of 4 cm and a length of 200 cm. For the experiments reported in this work a reaction zone of 140 cm was used. The EFR was electrically heated and the preheated gases were introduced through flow straighteners to ensure laminar flow conditions. The experiments were performed at a heated furnace temperature of 1273 K. The gas flow was set to 22.4 L/min, which corresponds to a residence time of 2.5 s. The amount of excess oxygen in the oxidant over the required stoichiometric oxygen was set to $O_{2,ex} = 25\%$. The excess oxygen was then used to calculate the required fuel mass flow rate, $\dot{m}_F = \dot{m}_{F,\mathrm{st}}/(1 + O_{2,\mathrm{ex}})$, where $\dot{m}_{F,\mathrm{st}}$ represents the stoichiometric fuel mass flow rate. Four different combustion atmospheres were employed: air ($21\%O_2/79\%N_2$), and three binary gas mixtures of O_2 and CO_2 ($21\%O_2/79\%CO_2$, $30\%O_2/70\%CO_2$ and $35\%O_2/65\%CO_2$).

Table 1
Proximate and ultimate analyses of the samples used in this work.

Sample	OW	HVN	SAB
Origin	Spain	Spain	S. Africa
Rank		sa	hvb
Proximate analysis (wt.%)			
Moisture	9.0	1.1	2.4
Volatile matter (db)	71.9	9.2	29.9
Ash (db)	7.6	10.7	15.0
Fixed carbon[a] (db)	20.5	80.1	55.1
Ultimate analysis (wt.%, db)			
C	50.2	81.9	69.3
H	6.1	3.1	4.2
N	1.8	1.7	1.8
S	0.2	1.4	0.8
O[a]	34.1	1.2	8.9
High heating value (MJ/kg, db)	19.9	31.8	27.8

sa: semi-anthracite; hvb: high-volatile bituminous coal.
db: dry basis.
[a] Calculated by difference.

Two coals of different rank were used in this work: a semi-anthracite from the Hullera Vasco-Leonesa in León, Spain (HVN); and a South African high-volatile bituminous coal from the Aboño power plant (350 MWe) in Asturias, Spain (SAB). A biomass, olive waste (OW) was also employed. This biomass is the solid waste that remains after the process of pressing and extraction of olive oil. The coal and biomass samples were ground and sieved to obtain a particle size fraction of 75–150 μm. The proximate and ultimate analyses together with the high heating values of the fuel samples are presented in Table 1.

The fuel samples in a hopper were fed into the EFR reaction zone through a cooled injector. The fuel particles were then injected into the centre of the preheated gas stream. The reaction products were quenched by aspiration in a stream of nitrogen by means of a water-

Table 2
Inputs of the CFD code for the gases and coal and biomass blends feed rates.

Atmosphere	Gas inlet (g/min)	Coal and biomass blends mass flow rate (g/min)					
		HVN-OW blends			SAB-OW blends		
		0%OW	10%OW	20%OW	0%OW	10%OW	20%OW
$21\%O_2/79\%N_2$	1.548	0.110	0.114	0.119	0.105	0.135	0.139
$21\%O_2/79\%CO_2$	2.118	0.110	0.114	0.119	0.105	0.135	0.139
$30\%O_2/70\%CO_2$	2.058	0.157	0.164	0.171	0.147	0.194	0.196
$35\%O_2/65\%CO_2$	2.016	0.182	0.190	0.198	0.175	0.225	0.231