Experimental Thermal and Fluid Science 34 (2010) 646–655

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Validation of a FBC model for co-firing of hazelnut shell with lignite against experimental data

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ARTICLE INFO

Article history:
Received 30 October 2009
Received in revised form 14 December 2009
Accepted 15 December 2009

Keywords:
Fluidized bed combustion model
Co-firing
Biomass
Lignite

ABSTRACT

Performance of a comprehensive system model extended for modelling of co-firing of lignite and biomass was assessed by applying it to METU 0.3 MW_t Atmospheric Bubbling Fluidized Bed Combustor co-firing lignite with hazelnut shell and validating its predictions against on-line temperature and concentration measurements of O_2, CO_2, CO, SO_2 and NO along the same test rig fired with lignite only, lignite with limestone addition and lignite with biomass and limestone addition. The system model accounts for hydrodynamics; volatiles release and combustion, char combustion, particle size distribution for lignite and biomass; entrainment; elutriation; sulfur retention and NO formation and reduction, and is based on conservation equations for energy and chemical species. Special attention was paid to different devolatilization characteristics of lignite and biomass. A volatiles release model based on a particle movement model and a devolatilization kinetic model were incorporated into the system model separately for both fuels. Kinetic parameters for devolatilization were determined via thermogravimetric analysis. Predicted and measured temperatures and concentrations of gaseous species along the combustor were found to be in good agreement. Introduction of biomass to lignite was found to decrease SO_2 emissions but did not affect NO emissions significantly. The system model proposed in this study proves to be a useful tool in qualitatively and quantitatively simulating the processes taking place in a bubbling fluidized bed combustor burning lignite with biomass.

1. Introduction

Fluidized bed combustion technology is an established technology developed for burning coal for energy generation due to its high system efficiency, fuel flexibility and easier control of pollutants such as SO_2 and NO_x. However, due to increasing demand of energy, depleting fossil fuel sources and gradual introduction of increasingly restrictive legislations on emissions from combustion sources have been increasing the interest in the utilization of biomass. Biomass is a renewable energy source since it can be considered as CO_2-neutral fuel as it consumes the same amount of CO_2 from the atmosphere during its growth as is released during its combustion. It also contributes to the reduction of SO_2 and NO_x emissions due to its low sulfur and nitrogen contents. Furthermore, when burned instead of landfilled, it prevents CH_4 release to atmosphere, which is a more powerful greenhouse gas compared to CO_2 [1].

However, some operational problems exist when biomass is burned alone. The most common problems encountered in industry and utility boilers are severe fouling, slagging and corrosion which are mainly originated from high alkali chloride content of biomass ash. These problems in biomass firing combustion systems can be alleviated by co-firing biomass with coal [2–5] which is a promising alternative that leads to an economical and environmentally friendly use of coals by reducing pollutant emissions as well as to the utilization of biomass residues [1,3,6–9].

To improve and optimize the operation of co-firing systems, a detailed understanding of co-combustion of coal and biomass is necessary, which can be achieved both with experiments and modelling studies. In literature, there are a number of experimental studies on co-combustion of biomass and coal in fluidized bed combustors (FBCs) [1,10–15]. However, there exists a limited number of studies on mathematical modelling of co-combustion of coal with biomass. Okasha [16] presented a steady-state model for bubbling fluidized bed combustion of straw–bitumen pellets of 15 mm diameter and 15 mm length compressed under pressure of 150 bar and made of a 1:1 blend of rice straw and bitumen. In this model, hydrodynamics, volatile release, char particle combustion and entrainment were taken into consideration. Main shortcomings of the model were absence of char population balance and pollutant species balances. Model predictions were found to be in good agreement with measurements obtained from a 0.3 m ID, 3.3 m height atmospheric bubbling fluidized bed combustor burning straw–bitumen pellets in silica sand.

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doi:10.1016/j.expthermflusci.2009.12.006

Nomenclature

C	concentration, mol cm^{-3}
E	activation energy, cal mol^{-1}
E_o	mean of activation energy distribution, cal mol^{-1}
$f(E)$	activation energy distribution function for devolatilization, mol cal^{-1}
h	individual heat transfer coefficient, cal cm^{-2} s^{-1} K^{-1}
k	thermal conductivity, cal cm^{-1} s^{-1} K^{-1}
$k(E)$	first-order reaction rate constant for devolatilization, s^{-1}
k_o	pre-exponential factor for first-order devolatilization rate constant, s^{-1}; pre-exponential factor for CO oxidation, (cm^3 mol^{-1})$^{0.8}$ s^{-1}
k_{CO}	reaction rate constant for CO oxidation, (cm^3 mol^{-1})$^{0.8}$ s^{-1}
r	spatial independent variable, cm
R	ideal gas constant, cal mol^{-1} K^{-1}; radius, cm
t	time, s
T	temperature, K

Greek letters

α	thermal diffusivity, cm^2 s^{-1}; multiplication factor, –
ε	emissivity of particle
σ	standard deviation of activation energy distribution, J mol^{-1}; Stephan–Boltzman constant, cal cm^{-2} s^{-1} K^{-4}
v	volatiles released, %
v_∞	ultimate yield of volatiles released, %

Subscripts

avg	average
d	char
g	gas
p	particle
s	surface

Another modelling study was carried out by Gayan et al. [11] for modelling of a circulating fluidized bed combustor co-firing coal with a forest residue, i.e. pine bark. In this model, hydrodynamics, devolatilization, char population balances, char and volatile combustion were taken into consideration. However, sulfur retention and NO formation were not taken into account. The model was applied to two CFB pilot plants (0.1 and 0.3 MW_t). However, the validation of the model was mainly limited to the comparison of the carbon combustion efficiencies predicted by the model and the ones obtained in the two pilot plants.

Recently, Kulah et al. [17] developed a comprehensive model by extending a previously developed system model, originally proposed by Selçuk and Ozkan [18] and later improved, extended and validated against experimental data by Selçuk and her colleagues [19,20], for modelling of biomass-lignite co-combustion in bubbling fluidized bed combustor. The predictive performance of the model was tested by comparing its predictions with on-line concentration measurements of O_2, CO_2, CO, SO_2 and NO along the METU 0.3 MW_t Atmospheric Bubbling Fluidized Bed Combustor (ABFBC), where typical Turkish lignite was co-fired with olive residue. Predicted and measured temperatures and concentrations of gaseous species along the combustor were found to be in good agreement.

In the aforementioned modelling studies, co-firing of coal with only three different types of biomasses was investigated. However, Turkey is one of the leader producers of hazelnut in the world accounting for 75% of the worlds' total production with 632,000 ha plantation and 570,000 tons of production in year 2007 [21]. Consequently, significant amounts of hazelnut shells are available to be used in co-firing applications and this necessitates a detailed understanding of co-combustion of lignite and hazelnut shell. Therefore, the absence of a modelling study on co-firing of lignite with hazelnut shell in fluid bed combustors on one hand and the recent trend in utilization of biomass with local reserves in industry and utility boilers on the other have led to the motivation of this study, which was to extend a comprehensive system model developed earlier by Kulah et al. [17] for modelling of co-firing of lignite with hazelnut shell. The predictive performance of the model was tested by comparing its predictions with on-line concentration measurements of O_2, CO_2, CO, SO_2 and NO along the METU 0.3 MW_t ABFBC test rig, where typical Turkish lignite was co-fired with hazelnut shell.

2. Model description

In this study, the model developed by Kulah et al. [17] was modified to model co-firing of lignite with hazelnut shell. The system model accounts for hydrodynamics; volatiles release and combustion, char combustion, particle size distribution for lignite and biomass; entrainment; elutriation; sulfur retention and NO formation and reduction, and is based on conservation equations for energy and chemical species. Seven chemical species, O_2, CO, CO_2, H_2O, SO_2, NH_3 and NO are considered in the model. For the sake of integrity, a brief summary of the model will be provided in the following sections. Modification of the volatile release sub-model for the incorporation of co-firing of hazelnut shell will be described in detail to draw special attention to different devolatilization characteristics of lignite and hazelnut shell.

2.1. Bed hydrodynamics

Bed hydrodynamics is described by using modified two-phase theory suggested by Grace and Clift [22] in conjunction with the model of Gogolek and Becker [23]. Gas and solids in emulsion phase and gas in bubble phase are assumed to be well-mixed and in plug flow, respectively. An integrated average mean bubble size found from the bubble size expression proposed by Mori and Wen [24], in the sections unoccupied by the tube bank and from constant and uniform bubble size determined by the clearance between horizontal tube bank is utilized. Bubbles are assumed to be free of solids.

2.2. Volatiles release and combustion

Volatiles are assumed to be released uniformly in the emulsion phase for both fuels. The amount released in bed is determined by using the volatile release model of Stubington et al. [25] as it has already been validated successfully by comparing its predictions with experimental data taken on the METU 0.3 MW_t ABFBC test rig fired with lignite and biomass [17,19,20]. In order to describe the devolatilization kinetics, the parallel independent reaction model of Anthony and Howard [26] is used. In this model, the volatile release for a particle at a radius is given by

$$\frac{v}{v_\infty} = 1 - \int_0^\infty \exp\left(-\int_0^t k(E)dt\right) f(E)dE \tag{1}$$