Applied Thermal Engineering 128 (2018) 539–550

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Effect of changing biomass source on radiative heat transfer during co-firing of high-sulfur content lignite in fluidized bed combustors

Cihan Ates, Nevin Selçuk *, Gorkem Kulah

Department of Chemical Engineering, Middle East Technical University, Universiteler Mahallesi, Dumlupinar Bulvari No: 1, Cankaya, Ankara 06800, Turkey

HIGHLIGHTS

- Chemical and optical properties of particles are dominated by coal ash particles.
- Biomass source affects the particle size distribution (PSD) in the freeboard.
- Change in PSD is found to be influential on radiative properties in co-firing.
- Change in biomass source may lead variations in wall heat fluxes and source terms.
- Variations in PSD should be minimized if multiple biomass sources are utilized.

ARTICLE INFO

Article history:
Received 11 April 2017
Revised 5 July 2017
Accepted 3 September 2017
Available online 13 September 2017

Keywords:
Biomass supply
Co-firing
Radiative heat transfer
Fluidized bed combustor
Boiler efficiency

ABSTRACT

In this study, effect of changing biomass source on radiative heat transfer during co-firing of high-sulfur content lignite in the freeboard of 300 kW_t Atmospheric Bubbling Fluidized Bed Combustor (ABFBC) is investigated by using an in-house developed radiation code based on Method of Lines (MOL) solution of Discrete Ordinates Method (DOM). The freeboard is treated as a 3D rectangular enclosure containing gray, absorbing, emitting gas with absorbing, emitting, anisotropically scattering particles surrounded by black/gray diffuse walls. Radiative properties of participating gases are evaluated by using Leckner's correlations and gray particle properties are calculated based on Planck's distribution from the spectral Mie solutions. Input data required for the model are provided from six combustion tests which were previously carried out for Çan lignite with 14, 35 and 50% thermal shares of olive residue and hazelnut shells in the fuel mixture for the same Ca/S ratio. The results show that changing the biomass source affects the radiative properties of the particles in the freeboard through the change of particle size distribution rather than optical properties, which may lead to significant variations in radiative wall heat fluxes and source terms.

1. Introduction

Gradual introduction of increasingly restrictive legislations on emissions from combustion sources has been increasing the interest in biomass combustion. However, biomass combustion brings with it some operational problems when burned alone. The most common problems encountered in industry and utility boilers are severe fouling, slagging and corrosion. Co-firing biomass with coal is a promising alternative which leads to reduce ash related problems in biomass combustion and at the same time provides an economical and environmentally friendly use of coals by reducing pollutant emissions [1,2]. Nevertheless, there remain technical issues associated with biomass supply, handling and storage in co-firing applications due to its low energy density, seasonal characteristics and scattered geographical distribution [3,4].

Biomass itself is usually cheap but the cost of transportation directly affects the economic feasibility of biomass co-combustion due to its low bulk density together with the high moisture content, which necessitates huge amounts of biomass to be transported for even a small share of total heat input [2]. Optimum biomass transport distances and means of transportation are shown to depend on the capacity of the power plant [3] and maximum distance over which biomass can feasibly be collected is found to be between 25 and 100 km for highway transportation [3,5–8]. In particular, it has been shown that railway conveyance is needed if the capacity of the plant is larger than 5 MW_e [3] to ensure economic and environmental feasibility, which may not always be accessible in the vicinity of the plant. One of the possible solutions to mitigate biomass shortages encountered at high plant

* Corresponding author.
E-mail addresses: cates@metu.edu.tr (C. Ates), selcuk@metu.edu.tr (N. Selçuk), gorkemk@metu.edu.tr (G. Kulah).

http://dx.doi.org/10.1016/j.applthermaleng.2017.09.011
1359-4311/

Nomenclature

c	speed of light (m/s)
g	asymmetry factor (–)
I	radiative intensity ($W\,m^{-2}\,sr^{-1}$)
I_b	blackbody intensity ($W\,m^{-2}\,sr^{-1}$)
k	imaginary part of complex refractive index (–)
k_t	time constant with dimension $(m/s)^{-1}$
L_m	mean beam length (m)
m	complex refractive index (–)
n	real part of complex refractive index (–)
$\mathbf{r}$	position vector (–)
r	coordinate axis in cylindrical geometry (–)
T	temperature (K)
$\bar{T}$	average temperature (K)
t	time
w	quadrature weight (–)

Subscripts

g	gas
i	quadrature point
ℓ	index for a discrete direction
ℓ'	incoming discrete direction
m	ordinate index
m′	incoming ordinate
p	particle
λ	wavelength (μm)
ν	wavenumber (cm^{-1})

Superscripts

m	ordinate index
m′	incoming ordinate
ℓ	index for a discrete direction
ℓ'	incoming discrete direction

Greek symbols

β	extinction coefficient (m^{-1})
γ	angular differencing coefficient (–)
ϵ	error tolerance (–)
ε_g	emissivity of the flue gas (–)
η	direction cosine (–)
Θ	scattering angle (rad)
κ	absorption coefficient (m^{-1})
λ	wavelength (μm)
μ	direction cosine (–)
ξ	direction cosine (–)
ρ_p	particle density (kg/m^3)
σ	scattering coefficient (m^{-1})
τ	optical thickness
ϕ	azimuthal angle (rad)
Φ	scattering phase function (sr^{-1})
ω	scattering albedo
$\mathbf{\Omega}$	direction of radiation intensity (–)

capacities is having access to different biomass sources within the geological boundaries designated by logistic constraints.

Changing the biomass source, on the other hand, should not or at worst slightly affect the performance of the boiler. Heat transfer has always been an important parameter in the design, operation and optimization of industrial combustors with and without biomass co-firing [9,10]. Recent studies in pulverized coal fired furnaces reveal that measured total/radiative heat fluxes are lower in the case of biomass co-firing compared to that of coal combustion under both air and oxy fired conditions and heat transfer to the walls decrease with increasing biomass content of the fuel for the same thermal input [11–17]. This decrease is correlated to high moisture content of the biomass, however, significant differences in heat fluxes are still observed when the biomass moisture content is one third of the coal moisture content [16], indicating that high moisture content of the biomass particles cannot be the only reason for the decreased heat fluxes. In an experimental study, it is shown that number of fine particles increases logarithmically with increasing biomass share for constant thermal input while the mass concentration of particles remains the same for all cases from 0% coal to 100% coal [18]. This finding is confirmed by another study performed in a pilot scale fluidized bed combustor [19]. Considering the dominant role of particles in radiative heat transfer in combusting systems [20–26], understanding the change in number of fine particles as well as particle properties such as density and chemical composition with alternating biomass sources is of key importance.

For co-firing fuels with different characteristics, fluidized bed combustion technology is usually indicated to be the best choice within the available technologies due to fuel flexible feature, uniform and low combustion temperature and high combustion efficiency [27–29]. Furthermore, fluidized bed combustors (FBCs) are widely used for combusting low quality fuels like lignite, which is not only the world's most abundant fossil fuel but also one of the two major indigenous sources of energy in Turkey with an estimated quantity of 15.6 billion tons of reserves [30]. Even though much effort has been placed in understanding the radiative heat transfer in FBCs, effect of biomass addition on radiative properties of particles has received little attention despite the important role of particles in radiative heat transfer and there is a lack of research addressing the effect of changing biomass source on radiative heat exchange taking place between the particle laden combustion gases and the heat transfer surfaces.

As Turkey is one of the main olive and hazelnut producers in the world with 1,768,000 and 412,000 tons of annual production respectively [31], significant amount of olive residue (OR) and hazelnut shell (HS) is available to be used as biomass in co-firing. Absence of studies on co-firing of indigenous lignite/biomass blends in bubbling 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, necessitate investigation of the effect of biomass addition on radiative heat transfer for alternating biomass sources. Investigation is performed through mathematical modeling by using the experimental data on six combustion tests previously performed in 300 kW_t Atmospheric Bubbling Fluidized Bed Combustor (ABFBC) test rig in Middle East Technical University [32]. Data on combustion tests were collected for lignite-limestone-biomass blends with about 14, 35 and 50% thermal shares of olive residue and hazelnut shells in the fuel mixture for the same Ca/S ratio. To the best knowledge of the authors, the influence of alternating biomass sources on radiative heat transfer is quantified and compared for the first time for fluidized bed combustors.

2. Description of the method

2.1. Atmospheric Bubbling Fluidized Bed Combustor (ABFBC) test rig

Tests were carried out on the 0.3 MW_t ABFBC test rig. The main body of the test rig is the modular combustor formed by five mod-