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Effect of recycled flue gas ratios for pellet type biomass combustion in a packed bed furnace

Md. Rezwanul Karim [a,b], Arafat A. Bhuiyan [a,b], Jamal Naser [a,*]

[a] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[b] Department of Mechanical & Chemical Engineering, Islamic University of Technology, Gazipur 1704, Bangladesh

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1. Introduction

In the last few decades, global industrialization has increased the consumption of energy enormously. Fossil fuels have been used as the main source of heat and power production [1] but it has impacted our environment through emission. In the last two decades, much efforts have been given to obtain sustainable ways of generating power by reducing emission but maintaining generation. It can be achieved by shifting the fuel sources from conventional fossil fuels to renewable energy sources. Biomass is considered as an inexpensive choice for thermal energy and electricity generation comparing with other renewable energy sources [2]. Combustion of biomass also releases carbon in the atmosphere but biomass is considered carbon neutral source because it recaptures same amount of carbon in growing. While there are arguments regarding time required for re-sequestration, CO_2 capture technologies [3,4] used for coal fired plants are used for the reduction of CO_2 emission from biomass fired plants also. There are several CO_2 capture technologies named as pre-combustion capture, post-combustion capture and oxy-fuel combustion which can be used for less emission effect on environment. Among these, oxy-fuel combustion technology is considered as very effective technology to decrease emission of several gases like CO_2, NO_x and SO_x [5,6].

In oxy-fuel combustion technology, fuel is burnt with pure oxygen and recycled flue gas (RFG) or CO_2 instead of burning with atmospheric air. A high concentration of CO_2 is produced in the flue gas, which can be separated and processed easily. New technologies are developing to reduce the energy penalty for O_2 production in a CO_2 capture plant [5]. Oxy fuel combustion affects the combustion system and many changes occurs in the furnace like change in flame temperature, radiation heat transfer and gas species concentrations due to the presence of excess CO_2. The reasons behind this are, higher density of the flue gas, higher specific heat capacity of CO_2, lower O_2 diffusion rate in CO_2 and higher emitting power of the flue gases. However, much work has been done for the improvement of oxy-fuel combustion [5–10].

Many experimental studies have been performed starting from laboratory scale furnace, pilot scale furnace to large scale furnace [11–18]. Liu et al. [11] have investigated pulverized coal combustion in air and in O_2/CO_2 mixture. He found that combustion in 30% O_2 and 70% CO_2 can yield the same flame temperature of combustion in air with the advantage of lower N to NO_x conversion, lower CO emission and improved char burnout. The flame propagation velocity of pulverized coal cloud under O_2/CO_2 combustion is studied experimentally by Suda et al. [12]. Kaß et al. [13] have investigated dry lignite combustion in a 0.5 MW test facility under oxy fuel process and found a reduction of combustion time due to high CO_2 concentration in the flue gas. Coal biomass co-firing in power plants has been given much importance in this decade and a large amount of research has been done. But there has been very limited work reported on co-firing under oxy-fuel condition. Arias et al. [18] have used an entrained flow reactor to investigate ignition and burnout of coal and biomass blends under oxy-fuel conditions. Smart et al. [16] have conducted an experiment to study coal biomass co-firing under oxy-fuel condition in a 0.5 MWt combustion test facility. Radiative and convective heat transfer and burnout performances were studied for the combustion of Russian and South African coal with Shea meal and saw dust at different co-firing mass fractions.

Numerical investigation can be used to analyse combustion process parameters under different working conditions for oxy-fuel furnace design and operation. Several numerical work has

* Corresponding author.
E-mail address: jnaser@swin.edu.au (J. Naser).

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Nomenclature

A_i	pre-exponential factor (s^{-1})
A_v	area-volume ratio (m^{-1})
C_p	specific heat (J kg^{-1} K^{-1})
C_{fu}/C_{pr}	combustion model constant
d_p	particle diameter (m)
d_{eq}	equivalent diameter (m)
D	diffusivity of the species in the mixture (m^2 s^{-1})
E_i	activation energy (J mol^{-1})
h	convection coefficient (W m^{-2} K^{-1})
H	enthalpy (J kg^{-1})
$i^{'}$	radiation intensity (W m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
K	char reaction constants (m s^{-1})
K_m	mass transfer constant (m s^{-1})
LH	latent heat (J kg^{-1})
M	molecular weight (kg $kmol^{-1}$)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
$\overline{\dot{r}_{fu}}$	fuel consumption rate (kg m^{-3} s^{-1})
R	ideal gas constant (J K^{-1} mol^{-1})
$\dot{R}_i'''$	generation or consumption rates of various components (kg m^{-3} s^{-1})
Re	Reynolds number (–)
Sh	Sherwood number (–)
Sc	Schmidt number (–)
S	source term (Wm^{-3})
S_a	stoichiometric air/fuel ratio
$\boldsymbol{s}$	cell face area (m^2)
T_s	solid temperature (K)
T_g	gas temperature (K)
T_{evap}	evaporation temperature (K)
t	time (s)
U_i	velocity in the ith direction (m s^{-1})
V	volume (m^3)
v	gas velocity (ms^{-1})
$\boldsymbol{v_s}$	solid velocity (ms^{-1})
x_i	spatial distance in the ith direction
$\overline{y_{pr}}$	mass fraction of product (kg/kg)
$\overline{y_{ox}}$	mass fraction of oxidizer (kg/kg)
$\overline{y_{fu}}$	mass fraction of fuel (kg/kg)
z_i	gas composition

Greek symbols

α	fraction of drying heat amount
ε	solid fraction (–)
$\in$	emissivity
η	permeability (m^2)
μ	gas viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (W m^{-1} K^{-4})
τ_R	turbulent time scale (s^{-1})
Υ	inertial loss (m^{-1})
φ	char oxidation parameter (–)
ϕ	variable of PDE's
Γ	diffusion co-efficient

been stated in the literature [19–28] for oxy-fuel coal combustion and oxy fuel co-firing of coal and biomass [29–34]. Al-Abbas and Naser [22–26] have modelled combustion of pulverized dry lignite using different air fired and oxy-fuel conditions in lab scale [23–26] and large scale [22] furnaces. He has demonstrated the change in flame ignition, species concentration and radiation heat transfer for several oxy-fuel combustion cases. He has also investigated change in SO_x, NO_x emission and effect of multi-step chemical reaction [24]. Bhuiyan and Naser [31–33] have completed comprehensive modelling of highly volatile biomass co-combustion with Russian coal under different oxy-fuel condition and biomass co-firing ratios in small scale and large scale furnaces. They have found, with the increase of biomass sharing, peak flame temperature decreases due to lower calorific value of biomass and unburned carbon in fly ash increases. Also, improved burnout is observed in higher biomass shared oxy-fuel combustion cases.

Biomass combustion is a complex issue as it differs from conventional fossil fuels due to its physical properties. Biomass combustion in a small scale packed bed furnace [2,4] is very much helpful to study the complex solid conversion mechanism inside the bed due to its simple design, lower running cost and fuel preparation needed. Experimental investigations to obtain detail in bed data from packed bed biomass furnaces have been limited [35–40] due to difficulties in measuring data from non-homogeneous bed. Authors have reported bed temperature, bed height, flame temperature, species concentration above the bed for variety of biomasses in different size and shape. Numerical modelling of packed bed biomass combustion is much helpful to analyse many variables of the process under different working conditions [41,42]. A variety of different model approaches have been presented but the common method is to divide the system into bed and freeboard. Available CFD codes can model the gas phase in freeboard but separate model is required for the bed simulation [43]. The bed has been solved using zero dimensional model [43], one dimensional model [44,45], two dimensional model [46–49] and three dimensional model [50–55] to estimate temperature, ignition rate, bed height, species concentration etc. These models includes sub models for various solid conversion processes, heat and mass transfer between solid and gas phases, bed movement [54–57] and for solving thermally thick particles [54,58].

From literature, it is found that, several experimental and numerical work has been conducted on oxy-fuel coal combustion and limited work on coal-biomass co-firing under oxy-fuel condition. But, no research work has been reported on individual biomass combustion under oxy-fuel condition in a small scale grate firing furnace. As available CFD codes can't model the bed combustion simulation of biomass fuel, it will be very much interesting to model the oxy-fuel biomass combustion in a small packed bed grate furnace. In this work a 3D numerical model for biomass combustion in packed bed furnace has been developed for studying the combustion phenomenon of biomass fuels under oxy-fuel condition. This model has been validated with the results of an experimental study for biomass combustion. Commercial CFD software AVL Fire is used for simulation of oxy-fuel biomass combustion. The physics of biomass transport and biomass combustion have been included through several user defined subroutines written by the authors. Several combustion cases under air fired and oxy-fuel condition (with three different O_2/CO_2 (RFG) ratios) have been studied to find the effect on overall flame temperature, species concentration, solid phase variables and ignition front propagation velocity. The optimum cases are discussed to have a good understanding of biomass bed combustion under oxy-fuel condition in both physical and chemical fields.