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A CFD MODELLING OF RADIATIVE PERFORMANCE IN CO-FIRING OF BIOMASS WITH VICTORIAN BROWN COAL IN INDUSTRIAL FURNACE

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ABSTRACT

This study presents the modelling of co-firing concept of biomass with Victorian Brown coal under the most promising carbon capture and storage (CCS) system called oxy-fuel combustion in a dedicated coal fired furnace located in Victoria, Australia. Three selected co-firing ratios (20%, 40% and 60% were modelled under air-firing and three different oxy-firing cases (25% OF, 27%OF and 29%OF). AVL Fire ver.2009.2 was used as modelling tool with some user-defined coding. Special attentions were taken to control the irregularities of biomass particles. Results were presented in terms of radiative heat flux on the furnace wall. With the increase of co-firing ratios; radiative heat flux reduced significantly. It is found that flame temperature falls down due to increase of biomass percentage. Lower calorific value of the biomass, large irregular shaped particles, and lower residence time causes incomplete combustion leading to lower the temperatures. The lower flame temperatures significantly contribute to the reduced radiative heat fluxes. Comparatively higher radiative heat fluxes were obtained for air-firing case. With the improvement of oxy-firing cases, comparatively higher values of radiative heat flux were observed.

INTRODUCTION

Day by day, the demand of energy is increasing significantly specially in the developing countries. In order to meet the demand, different countries contributing to global warming, pollutant emission etc during combustion of fossil fuels in power plants. Strict environmental laws are imposed for controlling the CO_2 emissions throughout the world. In order to meet the rules, one of the possible ways of reducing emissions is to use CO_2 neutral renewable energy sources. Biomass fuels are CO_2-neutral energy source (Sondreal, Benson et al. 2001). Biomass can be combusted directly or indirectly. A comprehensive modelling strategy is illustrated in Ref. (Karim and Naser 2014). Direct combustion of these resources is appropriate as it will not require any technological changes to the existing power plants.

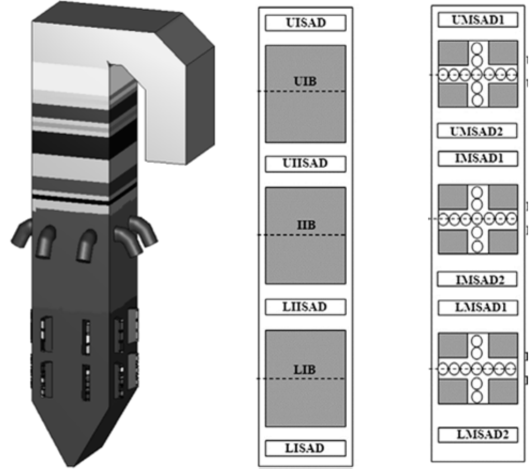
Research interest has been given to experiment the biomass combustion in laboratory/pilot and industrial scale facilities. The objectives of those studies were to investigate the ignition behaviours, species emissions, and ash formation characteristics. Different biomass fuel such as straw, Olive cake, Sewage sludge, wood chip, rice husk, bagasse, miscanthus cedar chip were used as a co-firing fuel with coal. It was found that with the increase in fraction of biomass sharing in the fuel supply, a significant reduction in emission was observed. Municipal solid wastes (MSW) were co-fired in several studies. The outcomes indicate that within the 40% MSW fraction, combustion efficiency drop of up to 8%. During most of the experiment, it was found that an operation range of 10-30% of biomass to coal ratio which is the optimum range for minimum pollutant emissions. In relation to the present concern of global warming, different CO_2 capturing technologies are developed such as pre-combustion capture, post-combustion capture, and oxy-fuel combustion. These strategies are to reduce CO2, NOx, and SOx emissions. Oxy-fuel combustion system is treated as the most prominent CO_2 capturing concept in the power generation sectors (Chen, Yong et al. 2012, Al-Abbas, Naser et al. 2013). In recent years, several experimental as well as numerical studies were conducted to investigate the performance of oxy-fuel technologies (Hjärtstam, Andersson et al. 2009, Smart, O'Nions et al. 2010, Smart, Patel et al. 2010, Edge, Gubba et al. 2011, Scheffknecht, Al-Makhadmeh et al. 2011).

From literature, it was found that a number of CFD modelling is available for coal combustion (Al-Abbas, Naser et al. 2011, Al-Abbas, Naser et al. 2012, Al-Abbas, Naser et al. 2013). Compared to that, only a few studies were concentrated for co-firing biomass with coal in industrial scale furnace. On the other hand, modelling of combustion of irregular shaped biomass particle is a challenging task. Several small scale investigations are attempted for the co combustion of biomass using CFD (Karampinis, Nikolopoulos et al. 2012, Nikolopoulos, Agraniotis et al. 2013, Álvarez, Yin et al. 2014, Bhuiyan and Naser 2015, Bhuiyan and Naser 2015). Co-firing of biomass and coal can be beneficial in reducing the carbon footprint of energy production. For the biomass particles having larger diameter, a computational sub-model for the heat transfer is developed by Gubba (Gubba, Ma et al. 2011). Few researchers' pointed to simulate the 3D large scale tangentially fired power generation plants using CFD (Bhuiyan and Naser 2015). Recent activities show the importance of various numerical as well as experimental studies of biomass co-combustion in industrial furnaces. It is vital to model the co-combustion phenomena in order to discover the potential problems that may occur during biomass co-firing and to mitigate potential negative effects of biomass fuels(Wei, Guo et al. 2012, Bhuiyan and Naser 2015). In this study, a tangentially fired boiler has been considered for modelling of the concept of co-firing of biomass with coal. For modelling purpose, a commercial computational fluid dynamic code AVL Fire 2009.2, with some user defined subroutines were used.

MODEL DESCRIPTION

Physical model setup

In the present study, a 550MWe furnace sited in the Latrobe Valley, Australia was considered for the study of co-firing concept by computational fluid dynamics (CFD) modelling. The information including dimensions, maximum operating conditions, unit productions of the utility furnace is summarised in Ref. (Al-Abbas, Naser et al. 2012, Al-Abbas and Naser 2013, Al-Abbas, Naser et al. 2013). The furnace considered in this study includes furnace hopper, several burners, water wall, hot gas off-takes (HGOT) port, several accessories like, economiser, superheater, reheater and a bifurcation to air heater. The schematic diagram of the computational model and used burner design is given in figure 1. The furnace consists of total eight mill-duct systems in four sides. Only five mills are in operation and the remaining mills are out of service. Mill duct system consists of several burners, secondary air duct system and hot gas off-take (HGOT) port. There are mainly two types of burner used, i.e.; Inert burner and main burner. Each burner is surrounded by several oxidizer flow system. The position of different burners and secondary air duct system and the orientations are presented in figure 1.



(a) (b) (c)

Figure 1: Schematic view of the (a). Computational model (b). Main burner and (c). Inert burner used in present study

Biomass sharing	Combustion cases			
	Air	Oxy-firing		
	AF	OF25	OF27	OF29
20%	A-1	B-1	C-1	D-1
40%	A-2	B-2	C-2	D-2
60%	A-3	B-3	C-3	D-3

Table 1: Different combustion cases considered

Properties	Coal	Biomass
Proximate analysis		
Volatile matter	50.5	74.7
Ash content	1.70	5.87
Fixed Carbon	47.8	19.4
Moisture content	62.0	2.80
Ultimate analysis		
C	67.7	52.3
H	4.63	6.40
N	0.52	0.20
S	0.30	0.00
O	24.9	41.1

Table 2: Fuel properties used in this study

Cases considered and particle distribution

In this modelling, three different co-firing ratios have been considered to investigate the radiative performance of the boiler under different combustion cases. Total three co-firing cases are: coal 80% and biomass 20%, coal 60% and biomass 40% and coal 40% and biomass 60% were simulated here. Regarding combustion environment, total four combustion environments such as air-firing (AF) (case A) and three different oxy-fuels (OF) combustion scenarios have been considered. The oxy-fuel cases are OF25, OF27 OF29. Each of the co-firing cases (cases 1-3) is simulated under all combustion environments. A case matrix is provided in table 1. The proximate and ultimate analysis of the Victorian brown coal and biomass particle is given in table 2. The distribution of fuel particles are based on the selected co-firing ratios considered in this study. The stoichiometric ratio (k) of the oxidizers to fuel equals to 1.18 was maintained for all combustion cases investigated. In the blend of fuel, a mixture of spherical and irregular shaped particle is considered. Coal particle is considered as spherical in size. The coal particles are in the range of 0.01-1.5mm. Biomass particle are assumed to be irregular in shape. Biomass particles are in the range of 0.09-3.0 mm. For biomass particles, length to diameter ratio was assumed as 10:1.

Boundary conditions

The chemical and physical set up of the furnace and operating conditions were entirely based on the station data for coal combustion under air-firing case only. In all the simulations, gas compositions were based on the numerical work by Al-Abbas (Al-Abbas, Naser et al. 2011, Al-Abbas and Naser 2012). The fuel, oxidizers, inert flue gas, water vapour, air, or/and O2/CO2 are supplied to the boiler through mill-duct systems to the prescribed incoming ports. In each burner, the fuel and gas were injected at a mass flow of 16.26 kg/s and 84.56 kg/s respectively. The mass flow rates and feed gas compositions through different burners for air firing (AF) and oxy-firing (OF) combustion cases considered in this study are given in Ref. (Bhuiyan and Naser 2015). The temperature of the burners and the secondary air duct systems were set to 397 K and 473 K respectively. Major wall boundaries are furnace zone wall, water tube wall, convection zone wall, and round duct wall. Prescribed wall temperatures for different sections are applied in this study. Different convection zone such as reheater, economiser, superheater are set to the values of heat absorption of 121.98 MW, 100.0 MW and 115.75 MW respectively. No-slip boundary condition (u, v, and w = 0) is applied for the wall surface. The temperature and emissivity of the wall surfaces are set to be 973 K and 0.71 respectively. At the exit, the entire variable gradients are set to zero for all the conditions.

MATHEMATICAL MODELLING

Modelling of co-firing of pulverised Victorian brown coal with different sharing of biomass under different operating conditions were conducted by a commercial CFD code AVL Fire version 2009.2. In this study, fluid and particle flow are described by the Eulerian/Lagrangian approach as given in Ref (Bhuiyan and Naser 2015).

$$\frac{\partial}{\partial t}(\rho\phi) + \frac{\partial}{\partial x_i}(\rho U_i \phi) = \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_i}\right) + S_\phi + S_{p\phi} \quad (1)$$

Eddy Breakup (EBU) model is applied for all the combustion modelling cases. This model determines whether O_2/fuel is in limiting condition or not. This model can be expressed by the following equation (Bhuiyan and Naser 2014):

$$\overline{\rho}\overline{r}_{fu} = \frac{C_{fu}}{\tau_R}\overline{\rho}\min\left(\overline{y}_{fu}, \frac{\overline{y}_{ox}}{S}, \frac{C_{pr}\overline{y}_{pr}}{1+S}\right) \qquad (2)$$

Discrete Droplet Method (DDM) is used for particulate phase modelling including momentum exchange, heat and mass transfer phenomena.

$$m_p \frac{du_{id}}{dt} = \vec{F}_{idr} + \vec{F}_{ig} + \vec{F}_{react} \qquad (3)$$

For turbulence modelling, k-epsilon turbulent model is considered (Bhuiyan, Islam et al. 2012, Bhuiyan, Amin et al. 2013, Bhuiyan, Amin et al. 2014, Bhuiyan, Amin et al. 2015). In order to consider the effects of the irregularities, a special shape factor is introduced for considering the drag effects for biomass fuel with proper formulation. The discrete transfer radiation method given in Ref (Lockwood and Shah 1981) is considered in this study has shown to be a very appropriate method for general radiation predictions which is easily embedded in overall CFD procedure. Fluid radiative properties modelling are uncoupled from DTRM and, depending on the problem; various models can be used for this. In the current study, the weighted sum of gray gases model is adopted for absorption coefficient modelling in non-homogenous combustion problems. The WSGGM is very important for gas radiation calculation especially in oxy-firing cases, where CO_2 and H_2O present in high concentration. In the present study, three steps homogeneous and heterogeneous chemical reactions (Al-Abbas and Naser 2012) have been considered for the modelling of devolatilization and char oxidation processes respectively.

Devolatilization (Homogeneous)

$$1.\ CH_4 + O_2 \rightarrow CO + H_2 + H_2O + \text{Heat} \qquad (4)$$

$$2.\ CO + H_2O \leftrightarrows CO_2 + H_2 \qquad (5)$$

$$3.\ O_2 + 2H_2 \leftrightarrows 2H_2O \qquad (6)$$

Char combustion (Heterogeneous)

$$C_{char} + \frac{1}{2}O_2 \rightarrow CO + \text{Heat} \qquad (7)$$

$$C_{char} + CO_2 \rightarrow 2CO \qquad (8)$$

$$C_{char} + H_2O \rightarrow CO + H_2 \qquad (9)$$

RESULT AND DISCUSSION

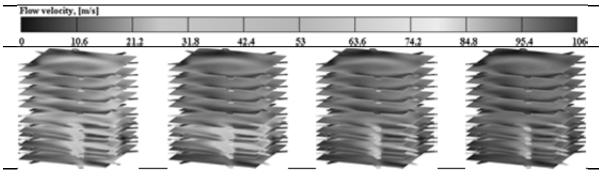
Figure 2 displays the velocity contours in the burner zone for 20% biomass cases under all combustion scenarios considered. It is found that comparatively reduced flow is detected in the hopper region for case B, C and D compared to case A. Alike findings have been perceived for temperature distributions at the identical area of furnace. This guaranteed that flow velocity has direct effect on the burning system. In the burner zone, the peak value of the average Z-velocity components for case A, case B, case C and case D are 18.02, 16.23, 15.08, and 13.01 m/s, respectively. In this study, coal biomass ratios are varied for different cases maintaining total fuel flow rate constant all the time. The flue gas temperature distribution in different burners in for 20% biomass sharing case at different burner is given in figure 3. It is seen from the figure that compared to inert burner, a higher flame temperature is observed in the main burner area for all the cases considered. It is found that the biomass particle burned out earlier in the furnace. Biomass particles seemed to be burned at a relatively higher rate in the burner area and burn quickly due to presence of highly volatile content. The peak flame temperature distribution at the burner area for all the case considered is given in table 3.

The O_2 and CO_2 distributions (kg/kg) in the X-Y plane for 20 % and 40% cases at the mid plane of selected air duct are presented in figure 4 and figure 5 respectively. The variation of O_2 and CO_2 is directly linked with flame temperature. Radiative heat fluxes on the furnace wall for all the cases considered in this study are displayed in figure 6. For the wall boundary condition, similar types of heat input are considered for the burner wall, combustion chamber and the convection and radiation heat transfer of the furnace wall. Figure presented the predicted wall incident heat flux on the radiation region of the furnace wall for all cases investigated. The total net radiative heat flux gradually increased for the oxy-fuel cases. This is due to improved O_2 concentrations and the decrease in the volumetric flow rates assumed in the oxy-fuel firing cases. Also with the increase of biomass sharing, radiative heat flux is significantly decreased. This can be explained similar to the case of flame temperature variations.

With the increase of biomass sharing in case 2 and 3 (air firing and oxy-firing), possibility of ignition of fuel within the furnace increases. Increase in the sharing of biomass corresponds to the increase in volatile content. Higher volatile contents generally produces more off-gases which

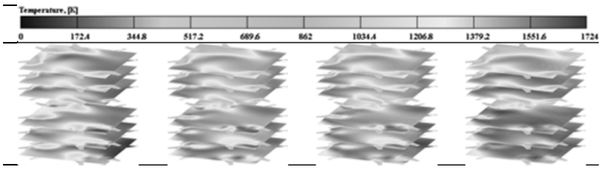
sharing	Combustion cases			
	Air Firing	Oxy-firing		
	AF	OF25	OF27	OF29
20%	1724	1700	1740	1801
40%	1643	1645	1686	1750
60%	1542	1600	1640	1710

Table 3: Peak flame temperature predicted in the main reaction zone of the furnace



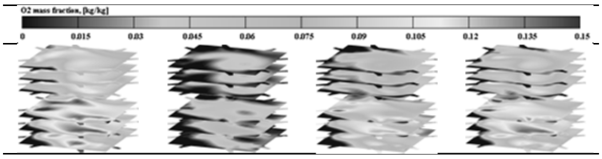
Case-A1 Case-B1 Case-C1 Case-D1

Figure 2: Velocity (m/s) distribution in different burners for 20% biomass & 80 % coal under different environment



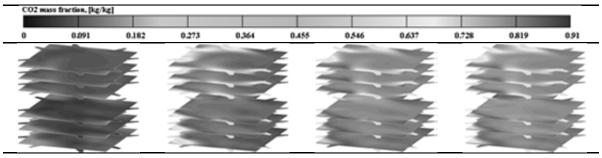
Case-A1 Case-B1 Case-C1 Case-D1

Figure 3: Temperature distribution in different burners for 20% biomass & 80% coal under different environment



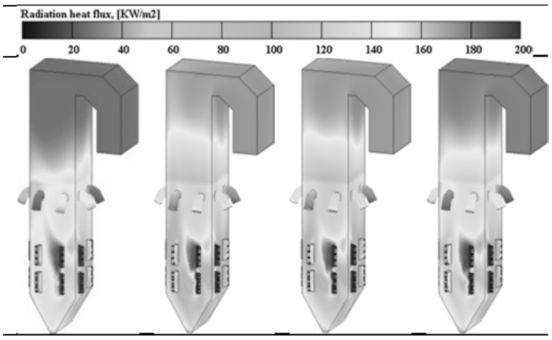
Case-A2 Case-B2 Case-C2 Case-D2

Figure 4: O_2 distribution in different burners 40% biomass & 60 % coal under different environment



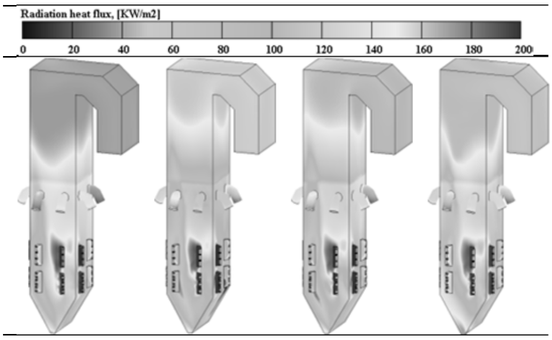
Case-A3 Case-B3 Case-C3 Case-D3

Figure 5: CO_2 distribution in different burners for 60% biomass & 40 % coal under different environment



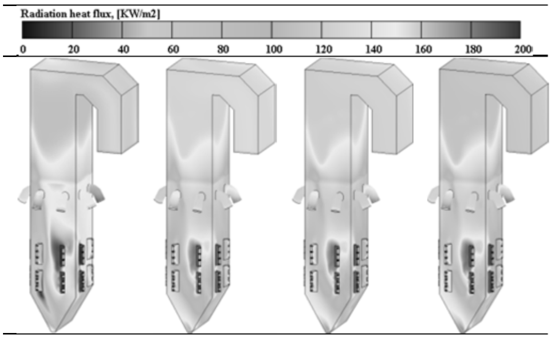
Case-A1 Case-B1 Case-C1 Case-D**1**

Figure 6(a): Radiative heat flux prediction for 20% biomass with 80 % coal under different environment



Case-A2 Case-B2 Case-C2 Case-D2

Figure 6(b): Radiative heat flux prediction for 40% biomass with 60 % coal under different environment



Case-A3 Case-B3 Case-C3 Case-D3

Figure 6(c): Radiative heat flux prediction for 60% biomass with 40 % coal under different environment

results larger volume of flames. Higher volatile content in higher sharing of biomass and the higher char reactivity of biomass compared to coal ensures the faster burning of biomass particle within the furnace. Though, higher volume of flames with lower temperatures is found with the increase of biomass sharing in all the cases leading to lower radiative heat flux. For different combustion cases, higher temperature range is found for co-firing case 1 compared to case 2 and 3. The dominant effect of the lower calorific value and moisture content of biomass dampens the effect of volatile content. Therefore the major effect of the lower calorific value of biomass contributes to lower radiative heat flux.

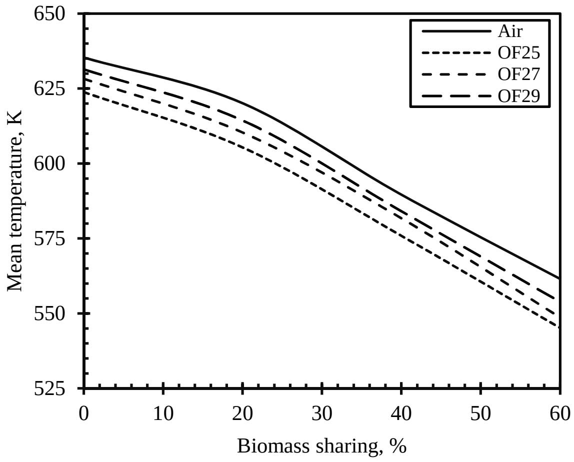


Figure 7: Temperature profile at furnace exit for different biomass sharing under air-oxy environment

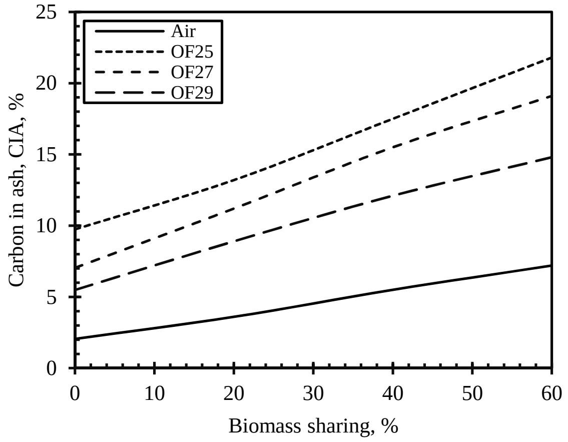


Figure 8: Carbon in ash predicted at furnace exit for different biomass sharing under air-oxy environment

Figure 7-8 presents the predicted CFD results including temperatures and unburned carbon for all the cases considered at the final exit of the furnace. With the increase of biomass sharing for each combustion cases, temperatures were decreased in air-firing case. This can be explained by the less moisture content of coal and lower calorific value of the biomass. With the increase of biomass sharing, a significant increase of unburned carbon in fly ash was predicted. The high amount of unburned carbon due to sharing of biomass is partially attributed to the large size of the biomass particles. Comparatively, improved burnout was observed with the increase of O_2 concentrations in oxy-fuel combustion cases. This can be attributed to longer residence times for the biomass and coal particles and higher oxygen concentration in the furnace. The increase in unburned carbon in ash with the increase of biomass sharing would reduce boiler efficiency. The CO_2 concentrations at the final exit of the furnace are same as to that of presented in the burner region.

CONCLUSION

A CFD modelling has been presented to inspect the characteristics of co-firing concept of pulverized coal and biomass particles in a 550 MWth tangentially fired furnace. Results were presented for three different biomass sharing under four different combustion environments. The confidence on this study was achieved from the model developed for a small scale furnace. Compared to the pure coal combustion, a decrease in the radiative heat flux with the increase of biomass particle flow is found which can be explained with the variation of flame temperatures.

Other results were presented in the form of peak flame temperature, flow distributions, O_2 and CO_2 distribution in the main reaction area. Unburned carbon, emissions and temperatures characteristics at the final exit of the furnace were evaluated. Comparatively improved burnout was observed in oxy firing cases. Unburned carbon in ash was predicted to increase when co-firing ratio increases due to the large size of the biomass particles.

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