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Numerical modelling of oxy-fuel combustion in a full-scale tangentially-fired pulverised coal boiler

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Abstract

This paper presents a computational fluid dynamics (CFD) modelling study to investigate Victorian brown coal combustion in a 550 MW utility boiler under the air-fired (standard) and three oxy-fuel-fired cases. The standard case was modelled based on the real operating conditions of Loy Yang A power plant located in the state of Victoria, Australia. A level of confidence of the present CFD model was achieved validating four parameters of the standard combustion case, as well as the previous preliminary CFD studies which were conducted on a lab-scale (100 kW) unit firing lignite and propane under oxy-fuel-fired scenarios. The oxy-fuel combustion cases are known as OF25 (25vol. % O_2 concentration), OF27 (27vol. % O_2 concentration), and OF29 (29vol. % O_2 concentration). The predictions of OF29 combustion case were considerably similar to the standard firing results in terms of gas temperature levels and radiative heat transfer compared with OF25 and OF27 combustion scenarios. This similarity was because of increasing the residence time of pulverised coal (PC) in the combustion zone and O_2 concentration in feed oxidizer gases. Furthermore, a significant increase in the CO_2 concentrations and a noticeable decrease in the nitric oxides (NO_x) formation were noted under all oxy-fuel combustion conditions. This numerical study of oxy-fuel combustion in a full-scale tangentially-fired PC boiler is important prior to its execution in real-life power plants.

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Keywords: Oxy-fuel combustion;Victorian brown coal; Combustion chemistry; CO_2 capture; NO_x emission; CFD.

1. Introduction

In general, approximately 85% of electricity production is obtained from solid fuel (coal) in Australia. In the Latrobe valley/Victoria, the Loy Yang power plant has been designed to use brown coal. This source of energy is a major contribution to the greenhouse gases (GHG) emissions. In order to keep a continuous usage of existing power plants and make them environmentally friendly, innovations and research on the brown coal combustion in tangentially-fired furnaces can play an important role to develop this economical energy source. In addition, with increasing concerns from the Kyoto Protocol against the global climate change, developments and research on the brown coal combustion can also make it meet a better sustainable progress for power plants (Chun-Zhu, 2004).

Recently, several advanced combustion technologies have been developed such as Pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture. These technologies are being considered as the most efficient utilization technologies to reduce CO_2, NO_x, and SO_x emissions and fuel consumption (Wall et al., 2009; Kakaras et al., 2007). However, oxy-fuel (O_2/CO_2) combustion technology has been widely considered the most viable technique in the PC power plants. The basic concept of the O_2/CO_2 technology is to use pure oxygen (approximately 95vol.% O_2), produced in air separation units, instead of air (O_2/N_2) in conventional combustion to burn fuel. Due to this high purity of O_2, a very high combustion temperature is achieved in the combustion zone. This elevated temperature can be diluted by recycling part of the flue gas (about 60-80%) to the furnace so as to decrease the radiation heat transfer to the furnace wall. At the end of this

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process, the partial pressure of carbon dioxide in the flue gas is highly increased; thereby the capturing process of CO_2 will be easier and economically efficient relative to that in the conventional firing. Nevertheless, NO_x and SO_x are decreased, and a high char burnout is achieved in the exit flue gas (Al-Abbas and Naser, 2012a).

Before switching to apply oxy-fuel combustion technique for conventional full-scale firing boilers, lab-scale furnaces have to be initially examined under a number of oxy-fuel combustion conditions. This strategy is strongly recommended to examine the combustion characteristics and boiler performance. Nevertheless, when the oxy-fuel combustion program was started in the last decade, much research has been carried out in terms of experimental investigations (Andersson, 2007) and numerical studies (Al-Abbas et al., 2011). The most important features of this work focused on the species concentrations, flame temperature levels, char burn-out, NO_x and SO_x formation, and heat transfer. The values of these variables, under oxy-fuel combustion conditions, are connected to the amounts and concentrations of oxygen and carbon dioxide used in the recycled flue gas (RFG). The differences in the thermodynamics properties between the CO_2, in oxy-fuel, and N_2, in the conventional firing atmosphere, can lead to some changes in the combustion characteristics inside the furnace. These amendments should be reduced as much as possible so as to be close to the characteristics of conventional combustion.

From the recent literature, there are a lot of innovations on oxy-fuel combustion technique, which implemented under several operating conditions and combustion environments to reduce the retrofits for the conventional combustion system. However, in the present simulation study, the oxy-fuel combustion approach that conducted experimentally in the Chalmers' lab-scale furnace (Andersson, 2007) has been chosen. This selection was dependent on the preliminary CFD studies (Al-Abbas and Naser, 2012a and b). Whilst the existing (reference) combustion case has been simulated based on the drawings and operation conditions of Loy Yang A power plant that provided by the Energy Technology Innovation Strategy (ETIS) program (Staples and Marshall, 2010). A CFD code, AVL Fire version 2008.2, was used to model and analyze four different combustion environments. Four combustion scenarios were simulated: standard PC combustion, and three oxy-fuel combustion cases, which are known as OF25, OF27, and OF29. User-defined functions (UDFs) required for the PC devolatilization, char burnout, multi-step chemical reactions, mass and heat transfer, carbon in fly-ash, and nitric oxidizes formation/destruction have been written and incorporated into the CFD code. Results, for all combustion cases investigated, are compared. The species concentrations, temperature distributions, gas-phase velocity fields, char burnout, NO_x emissions, and radiative heat transfer obtained for all combustion cases were compared.

2. Model description and methodology

2.1. Geometry and operating conditions of the boiler

The tangentially-fired Victorian (Australian) brown coal 550 MW_e boilers located in the Latrobe Valley mine, was used in this simulation study. The geometric description of the CFD model for the boiler, Loy Yang A, is shown in Figure 1a. The unit produces 430 kg/s of steam flow at 16.8 MPa and 540 ^oC under full load of operating conditions. In Figure 1, the CFD model was extended from the furnace hopper up to the top of the tower. The geometric dimensions of the simulated boiler were 98.84 m, 17.82 m, and 17.82 m for the height, width, and depth, respectively.

The furnace used in this study consists of eight mill-duct systems, two on each side face of the furnace. Only five mills (numbers 1, 2, 5, 6, and 8) are in service and the remaining mills are out of service (numbers 3, 4, and 7). There are three inert burners and three main burners for each mill-duct system. The mill-duct systems are designed for the following purposes: grinding the raw coal into pulverized coal (PC) in the mill, removing the moisture content (62% wt) from the brown coal through the drying shaft, transporting and distributing the PC. The centrifugal separation system is used to deliver pulverized coal from the grinding mill to the inert and main burners of the furnace. This distribution of fuel and gases (fuel-rich mixture) to the main burners is required to maintain combustion stability in the furnace.

Table 1 shows the mass flow rates (kg/s) of air (O_2/N_2) and O_2/CO_2 for the reference (air-fired) and the oxy-fuel combustion scenarios, respectively at each secondary air duct. In the furnace zone, the burners' arrangements on the furnace wall surface were as follows from top to bottom: upper inert burner (UIB), intermediate inert burner (IIB), lower inert burner (LIB), upper main burner (UMB), intermediate main burner (IMB), and lower main burner (LMB). The locations, reference levels (R.L.), of the above-mentioned burners are based on the original ground level of the power plant. The secondary air port ducts were set up above and below each burner in order to improve combustion characteristics. A schematic demonstration of the secondary air ports, in the inert burners, was as follows from top to bottom: upper inert secondary air duct (UISAD), upper intermediate inert secondary air duct (UIISAD), lower intermediate inert secondary air duct (LIISAD), lower inert secondary air duct (LISAD). While in the main burner, the schematic demonstration of the secondary air ports was shown as follows: upper main secondary air ducts 1 and 2 (UMSAD1& 2), intermediate main secondary air ducts 1 and 2 (IMSAD1& 2), and lower main secondary air ducts1 and 2 (LMSAD1& 2). In order to control the air flow distribution in the central zone of the main burners, a core air duct is installed in the middle of each PC burner, i.e. upper, intermediate, and lower core secondary air ducts (UCSAD, ICSAD, and LCSAD). In representing the convection zone, eight different sources of heat sinks were implemented above the location of hot gas off-takes (HGOTs).

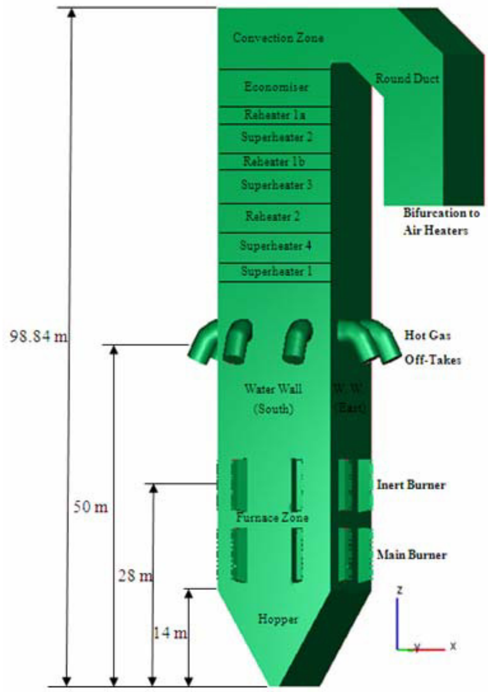

Fig. 1. The geometric description of the CFD model for the boiler, unit 1 at Loy Yang A power station.

Table 1. The mass flow rates (kg/s) of air (O_2/N_2) and O_2/CO_2 for the reference (air-fired) and the oxy-fuel combustion scenarios at each secondary air duct.

Secondary air duct	Distribution ratio (%)	Combustion cases			
		Standard Air-Fired	Oxy-Fuel OF25	Oxy-Fuel OF27	Oxy-Fuel OF29
		Mass flow (kg/s)	Mass flow (kg/s)	Mass flow (kg/s)	Mass flow (kg/s)
Upper inert	5.0%	6.89	5.71	5.3	4.96
Upper intermediate inert	5.0%	6.89	5.71	5.3	4.96
Lower intermediate inert	5.0%	6.89	5.71	5.3	4.96
Lower inert	5.0%	6.89	5.71	5.3	4.96
Upper main	20.0%	27.55	22.87	21.21	19.84
Upper core	6.67%	9.19	7.62	7.07	6.61
Intermediate main	20.0%	27.55	22.87	21.21	19.84
Intermediate core	6.67%	9.19	7.62	7.07	6.61
Lower main	20.0%	27.55	22.87	21.21	19.84
Lower core	6.67%	9.19	7.62	7.07	6.61
Total		137.78	114.35	106.09	99.2

2.2. Numerical description

The geometric model was precisely constructed using the CAD tool, and the dimensions of model geometry were taken from the power plant drawings. The first step of this simulation has been conducted solving of the governing equations of combustion, heat and mass transfer, and turbulent flow under transient mode. The solutions are repeated for all variables in each control volume until the usual convergence limit was achieved with less than 10^{-4}; the CFD code is based on the finitevolume approach. For the convergence criteria, simulations were run up to 48,000 time-steps until the stable quasi steady state was reached. Then, the numerical results were averaged over the final 8,000 time-steps. After the converged solution was achieved for the two-phase (gases and particles) flow, the second step of the simulation was subsequently implemented for the NO_x formation/destruction models.

The standard SIMPLE algorithm was used solving the combination between the velocity and pressure in Navier-stokes equations. A Lagrangian/Eulerian approach was used for gas-solid two-phase flow. Under the initial simulation set up, the time-step used in this simulation was limited to 0.0005 (s) in order to allow for the temperature profile to stabilize. Once the simulation results become more stable, the time-step is increased up to 0.0025 (s), an appropriate value by the numerical stability. The total number of particles used in this simulation was 50,000 particles, and the share of each in the service mill-duct system was 10,000 particles. In the convection zone of the furnace, heat absorption sources for the water tube wall and the convective tube banks were simulated as heat transfer sink terms (user defined sinks) in the enthalpy equation.

3. Results and discussion

3.1. Temperature distributions

In Figure 2, the distributions of flue gas temperatures are showed along the height of the furnace at the mid cut of X-Z plane for the air-fired, OF25, OF27, and OF29 combustion scenarios. As soon as the reaction processes between PC and oxidizer gases have been started the flame temperature is gradually increased to be at a peak value in the furnace zone as follows: 1591.37 K for air-fired, 1479.0 K for OF25, 1540.3 K for OF27, and 1592.0 K for OF29. It is clearly seen that a reduction in the levels of the gas temperature when the N_2 is replaced by the CO_2 in the secondary air ducts, particularly in the OF25 and OF27cases examined. That obvious decrease in the gas temperature was mainly due to the higher volumetric heat capacity of CO_2 compared to N_2 in the gas mixture. On the other hand, the maximum gas temperatures between air-fired and OF29 combustion cases were approximately identical. That improvement on the gas temperature of the latter oxy-fuel case was because of increasing O_2 concentration in the feed oxidizer gases. However, the inlet flow fields of feed oxidizer gases (O_2/CO_2), in all oxy-fuel cases, were reduced in proportion to the volumetric flow rates by fixed ratios: 83%, 77%, and 72% for OF25, OF27, and OF29, respectively with respect to the conventional firing case.

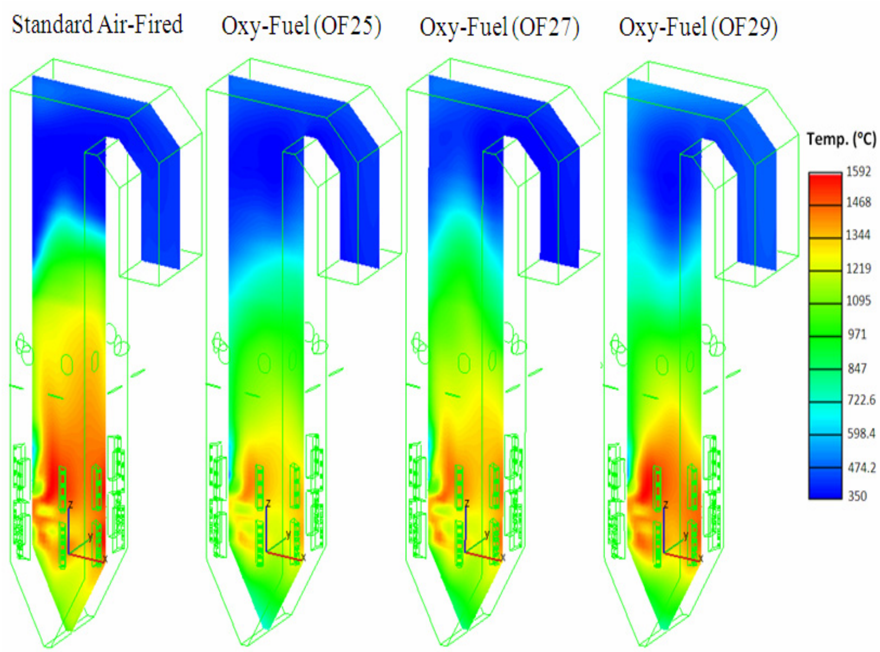

Fig. 2. Distributions of the flue gas temperature (K) along the height of the furnace at the mid cut (X-Z plane) for air-fired, OF25, OF27, and OF29 combustion cases.

Figure 3 presents the average flue gas temperature profiles along the furnace centreline, from bottom of the hopper up to the convective tube banks' location, for all combustion scenarios. As seen in the hopper region (level Z=0 m to level Z=14 m), the gas temperatures are low for all O_2/CO_2 cases compared to that of the conventional firing case. This phenomenon might be due to the availability of oxygen, in this region of the furnace, in the air-fired case. In contrast, no air leakage is considered in all O_2/CO_2 cases, and thus nearly no combustion occurs in the hopper zone. In Fig. 3, two peak gas temperatures exist in the furnace zone. The first peaks appear in the zone close to the main (PC) burners, which considered the fuel-rich mixture region in the furnace. Whilst the second peak values were approximately in the inert burner region, around level Z=28 m. These higher gas temperatures resulted in the reaction between the volatile matters released from the coal and surrounding oxygen, and thus a high amount of heat is generated. After that increase of the gas temperature in the burners region, the value gradually falls due to the heat absorption sinks of the furnace water wall and heat exchanger tubes at the upper zone of the boiler. Also observable in Fig. 3 is that despite similarities in the distributions of gas temperatures, 25% O_2/75% CO_2 mixture case showed low temperature values than other cases, in particular in the furnace zone.

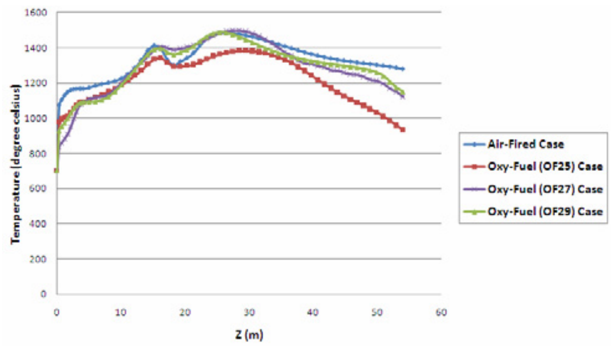

Fig. 3. Profiles of the mean flue gas temperature (K) along the furnace centreline for all combustion scenarios.

3.2. Species concentrations (carbon dioxide)

Figure 4 shows the profiles of carbon dioxide mass fraction (kg/kg) along the furnace centreline (from bottom of the hopper up to the convective tube banks' location) for all cases examined. For all oxy-fuel cases, the values of the CO_2 concentrations were approximately similar along the furnace centreline. In addition, the thermal dissociation mechanism of CO_2 adopted is clearly noticed in the furnace zone (level Z=14 m to level Z=25 m), particularly in the air-fired case. The differences in the CO_2 concentrations between the conventional combustion case and oxy-fuel cases are evident because of adopting the Chalmers' approach in this study. Approximately five times higher CO_2 is achieved for all oxy-fuel combustion scenarios compared to the air-fired case. The concentrations of CO_2 mass fractions at the furnace exit were equal to 18.84, 85.76, 85.01, and 84.18 wt% for the air-fired, OF25, OF27, and OF29, respectively. Due to the higher capability of carbon dioxide to absorb the combustion heat, this elevated CO_2 in the oxy-fuel cases can potentially increase the protection of the furnace wall against the hot flue gases.

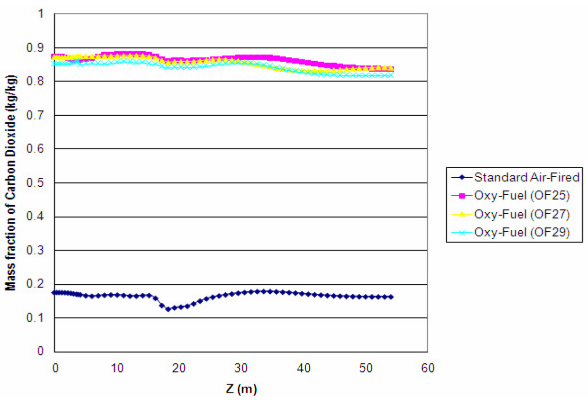

Fig. 4. Profiles of carbon dioxide mass fraction (kg/kg) along the furnace centreline (from bottom of the hopper up to the convective tube banks' location) for all combustion cases examined.

3.3. NO_x emissions

Figure 5 presents the distributions of nitric oxides (NO_x) ppm at the UMB plane and at the UIB plane for all combustion cases. In Fig. 5, there is a significant decrease in NO_x formation in all oxy-fuel combustion scenarios compared to the standard firing case. This reduction can be attributed into two main reasons: firstly due to decrease in the gas temperatures in the combustion zone; secondly due to the suppression of the thermal NO mechanism. It can be seen in Fig. 5 for oxy-fuel combustion cases, the conversion rates of coal-N to NO_x are somewhat increased with oxygen concentrations in the feed oxidizer gases. The concentrations were 375, 180, 240, and 280 ppm, under dry conditions, for the standard (air-fired), OF25, OF27, and OF29 cases, respectively.

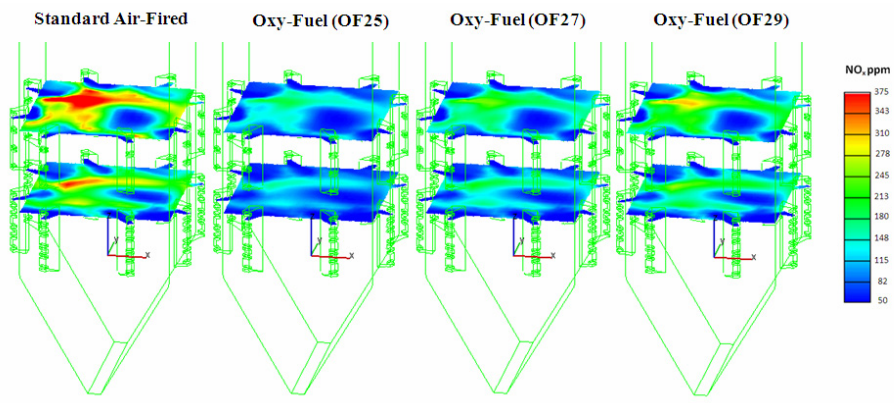

Fig. 5. Distributions of NO_x (ppm) at the UMB plane and at the UIB plane for all cases investigated.

4. Conclusion

In this study, a commercial CFD code, AVL Fire ver.2008.2, has been modified to investigate the Victorian brown coal combustion in a 550 MW tangentially-fired boiler under different combustion media. The obtainable experimental data were used to validate the numerical results under the standard firing condition, a good agreement is achieved. The oxy-fuel combustion approach adopted in a 100 kW facility unit (Chalmers' furnace) was applied to the present large-scale furnace in three oxy-fuel-fired conditions, namely OF25, OF27, and OF29. In the OF25 and OF27 combustion cases, a clear reduction in the gas temperatures was noted compared to the standard firing case. In contrast, OF29 case showed similar gas temperature levels and radiative heat transfer to that of the standard firing case. This is due to augmenting the residence time of coal particles and oxygen concentrations in the gas mixture.

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