Computational fluid dynamic modelling of a 550 MW tangentially-fired furnace under different operating conditions

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Abstract

In the present paper, a computational fluid dynamics (CFD) modelling study was performed for the combustion of the brown coal in a large-scale tangentially-fired furnace (550 MW) under different operating conditions. The AVL Fire CFD code has been used to model the furnace. The mathematical models of coal combustion with the appropriate kinetic parameters were written and added to the code as user defined functions. It consists of pulverised coal (PC) devolatilization, char burnout, heat and mass transfer, and nitric oxide formation. The simulation of the PC combustion was carried out using multi-step reaction chemistry schemes. The level of confidence of this numerical model was based on the previous validations of the lignite combustion in a lab-scale furnace, as well as the validation parameters of the present furnace at the standard existing conditions in terms of temperature values and species concentrations. Performance of the boiler under different operating conditions was investigated, from which the effects of air and coal mass flow rates were considered at full load with different operating schemes of coal mills (out-of-service operations). The validated model was used to perform the following investigation parameters: furnace gas temperatures, species concentrations (CO and CO\textsubscript{2}), and velocity distributions. This study provides good information to optimize the operations of the utility tangentially-fired boiler with less emissions production.

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1. Introduction

In the state of Victoria in Australia, there is one of the largest basins of brown coal over the world. This vast reserve of brown coal will lead to continuing the low-cost of electricity in the foreseeable future. It is, however, a competitive resource of energy amongst the other sources of fossil fuel and renewable energies. On the other hand, it has a major contribution to the greenhouse gases (GHG) emissions and global warming (Dodds et al., 2011).

In order to design such efficient, clean, and economical brown coal combustion systems, the understanding of the brown coal reactivity and behaviour under different operating conditions is required. Generally, brown coal has a number of advantages such as abundance, low-cost, high reactivity, and low sulphur content. In despite of these benefits, a high moisture content (about 60-70 wt %) is the major disadvantage of brown coal. However, in the existing pulverized brown coal (PC) tangentially-fired boiler, a large amount of the hot exit flue gas, typically 50% of the total flue gas generated, is reused to dry the brown coal within the mill-duct system. During that drying process by the hot gas off-takes (HGOTs), a large amount of water vapour is reproduced as well. In order to avoid any flame stability problems inside the combustion chamber, due to that evaporated steam, a fuel-rich mixture (mainly pulverized coal) is passed through the main burner ducts. Whilst a fuel-lean mixture, including water vapour, inert gases, and remaining of PC, is delivered to the inert burner ducts (upper burners). This distribution of the PC and inert gases into the firing system is favorable, particularly in this type of combustion technology (Ahmed and Naser, 2011).
Computational fluid dynamics (CFD) modelling studies can comprehensively provide a wide range of information for the design of furnace and burner that can reduce the cost of time-consuming experimental investigations. The CFD has the ability to predict well the flame structure, gas temperatures distributions, chemical species concentrations, radiative heat transfer etc., under different combustion conditions. The work programme covered by this paper achieves the development and validation of the computational tool applied to the combustion system which indicates the practical relevance and the long term viability for such a tool.

Currently, few numerical works on full scale boilers have been conducted. Therefore, the objective of this study is to simulate the brown coal combustion in a large-scale tangentially-fired furnace under several operating conditions. A computational fluid dynamics (CFD) code, AVL Fire version 2008.2, was used to model and analyze ten different combustion environments. The investigated combustion cases were dependent on the scenarios of change in the mass flow rates and distribution ratios for the PC and air, as an oxidant. In addition, the operation schemes of turned off (out-of service) burners were also examined under full load operation. The species concentrations (O2, CO2, CO, H2O, and H2), furnace gas temperature distributions, and velocity fields obtained for all combustion cases were compared.

2. Boiler description and operating conditions

The mesh generation with the geometric description of the CFD model for the boiler, unit 1 at Loy Yang A, is shown in Figure 1a. Under maximum continuous rating (MCR) of operating conditions, the unit produces 430 kg/s of steam flow through the main steam piping at 16.8 MPa and 540 oC. The computational domain illustrated in Figure 1 was extended from the furnace hopper up to the top of the tower, passing through the transition of round duct to before the bifurcation at the inlet to the air heaters. In this CFD model, the geometric dimensions of the simulated boiler were 98.84 m (height), 17.82 m (width), and 17.82 m (depth).

The tangentially-fired furnace used in this study consists of eight mill-duct systems, two on each side face of the furnace. For each mill-duct system, there are six separate burners, including three inert burners and three main burners, as well as a hot gas off-take (HGOT) that uses to dry the brown coal. The distribution of PC at both the burner mouths was accompanied by the inert flue gas and water vapour from the drying process in the mill. Around 82% of the PC and 34% of the gases is delivered to the main burner (PC burner) and the remaining 18% of pulverized coal and 66% of the gases is transported to the inert burner (vapour burner).

Regarding the operating conditions, the operating schemes of turned off (out of service) burners under full load operation are summarized in Table 1. Around 81.3 kg/s of PC and 422.8 kg/s of gas mixture are passed through both the inert and...
main burners of the furnace at different flow distribution ratios under the standard operating conditions (as specified in cases 1—6).

Table 1: Operation scheme of turned off (out of service) burners under full load operation and 20 % lower and 20 % higher than the standard operating conditions.

| Combustion case no. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Burners turned off  | 3, 4, and 7 | 3, 4, and 6 | 3, 4, and 8 | 1, 3, and 4 | 3, 5, and 7 | 2, 4, and 6 | 3, 4, and 7 | 3, 5, and 7 | 3, 4, and 7 | 3, 5, and 7 |

| Combustion scenarios | Standard operating conditions | Lower by 20% | Higher by 20% |
|----------------------|-------------------------------|--------------|--------------|

Table 2 shows the mass flow rates (kg/s) of air for the standard case and investigated combustion cases at each secondary air duct. The overall number of vapour and PC burners was 48, while 18 of the total burners were practically out of service. Regarding the burner configuration, each burner ports 1, 3, 5, and 7 were inclined by 24° with the perpendicular line to the furnace face, while each the remaining burner ports 2, 4, 6, and 8 were inclined by 30°. This configuration of the burner setup was mostly used in this type of tangentially-fired furnace in order to improve flame stability inside the furnace, as schematically plotted in Figure 1b.

Table 2: The mass flow rates (kg/s) of air for the standard case and investigated combustion scenarios at each secondary air duct.

| Secondary air duct | Distribution ratio (%) | Air Standard | 20% Lower | 20% Higher |
|--------------------|------------------------|-------------|-----------|------------|
|                    |                        | Mass flow (kg/s) | Mass flow (kg/s) | Mass flow (kg/s) |
| Upper inert        | 5.0%                   | 6.89        | 5.51      | 8.27       |
| Upper intermediate inert | 5.0%       | 6.89        | 5.51      | 8.27       |
| Lower intermediate inert | 5.0%       | 6.89        | 5.51      | 8.27       |
| Lower inert        | 5.0%                   | 6.89        | 5.51      | 8.27       |
| Upper main         | 20.0%                  | 27.55       | 22.04     | 33.07      |
| Upper core         | 6.67%                  | 9.19        | 7.35      | 11.03      |
| Intermediate main  | 20.0%                  | 27.55       | 22.04     | 33.07      |
| Intermediate core  | 6.67%                  | 9.19        | 7.35      | 11.03      |
| Lower main         | 20.0%                  | 27.55       | 22.04     | 33.07      |
| Lower core         | 6.67%                  | 9.19        | 7.35      | 11.03      |
| Total              |                        | 137.78      | 110.21    | 165.38     |

3. Mathematical models and numerical description

Numerical simulation of pulverized Victorian brown coal under the air-fired and oxy-fuel combustion conditions were carried out by a computational fluid dynamics (CFD) code. Appropriate subroutines were integrated and incorporated into the CFD code to account for devolatilization and char burnout, convection and radiation heat transfer between particles and gases, and thermal and fuel NO formation/destruction. The mathematical models and results of NOx formation are not shown in this paper. The devolatilized hydrocarbon fuel is considered as a methane equivalent, as there are no crucial differences between methane and the gaseous product attained from devolatilization of coal utilized. For precise calculations, the multi-step reaction mechanisms are carried out in this simulation study. The main reactions of the coal combustion model can be, however, expressed in three homogeneous and three heterogeneous chemical reactions, as follows: The chemical equations for devolatilized methane burned with oxygen, in a three-step reaction, are given in below:

\[
\text{CH}_4 + \text{O}_2 \rightarrow \text{CO} + \text{H}_2 + \text{H}_2\text{O} + \text{heat} \quad (1)
\]

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \quad (2)
\]
\[ \text{O}_2 + 2\text{H}_2 \rightarrow 2\text{H}_2\text{O} \quad (3) \]

While the chemical equations for char burned with oxygen, carbon dioxide, and water vapour are written as follows:

\[ \text{C}_{\text{char}} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO} + \text{heat} \quad (4) \]

\[ \text{C}_{\text{char}} + \text{CO}_2 \rightarrow 2\text{CO} \quad (5) \]

\[ \text{C}_{\text{char}} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \quad (6) \]

For the gas phase flow, non-steady state Eulerian partial differential equations (PDEs) were solved for mass, momentum, enthalpy, a number of species mass fractions, and turbulent fields. Turbulence is modelled using the standard k - \(\varepsilon\) turbulent model, which has been demonstrated a sufficient accuracy in the turbulent flow calculation, particularly in the near-burner region of previous simulation study (Al-Abbas and Naser, 2012). The eddy-breakup (EBU) turbulent combustion model is used to control the mixing rate of species. A number of mathematical models were coupled through the source terms of PDEs for calculating the coal devolatilization and char combustion models, turbulence, coal particle temperatures and trajectories, and the heat transfer models.

The coal combustion has been modelled, in this study, by using two main complex reaction processes. Firstly, the first order reaction model of Badzioch and Hawksley, 1970 is applied to calculate the rate of production of the volatile released. The pre-exponential factor and activation factor of the Arrhenius form are \(0.2 \times 10^5\ \text{s}^{-1}\) and \(5941\ \text{J.\text{kmol}^{-1}.\text{K}^{-1}}\), respectively, taking from the work of Anthony et al., 1975. Secondly; the char oxidation rate is modelled by a global diffusion control power-law, which was proposed by Field et al., 1967. In this heterogeneous reaction, the oxidation rate of the char is governed by the diffusion of bulk oxygen partial pressure to the particle’s external surface. The pre-exponential factor and activation factor of this model are equal to \(497\ (\text{kg.\text{m}^{-2}.\text{s}^{-1}.(N.m^{-2})^{-1}})\) and \(8540\ (\text{J.\text{kmol}^{-1}.\text{K}^{-1}})\), respectively. Regarding the heat transfer models, the discrete transfer radiation method (DTRM) has been used because of its ability for a better prediction in participating media, especially in furnaces.

4. Results and discussion

4.1 Temperature distribution

Figure 2 presents the effects of different operating conditions on the flame shape in the combustion zone at the 1650K iso-surfaces for all combustion cases examined. The effects of different turned off burners operations under full load are presented in panels (a)-(f), while in panels (g)-(j) the effects of mass flow rates and distribution ratios for the brown coal particles and mill gases are investigated. That was done by using the validated CFD model (Al-Abbas et al., 2012) under two different combustion scenarios: 20 % lower (cases 7 and 8) and 20 % higher (cases 9 and 10) than the standard combustion case, as shown in Tables 1 and 2. This iso-surface temperature can clearly show the flame distributions in the furnace and determines as a result the boiler performance at different combustion conditions. The operation scheme of the combustion cases used in this study was basically dependent on the inclined angles of each burner ports, as schematically plotted in Fig. 1b. However, this strategy of testing is used to improve the turbulent mixing of PC with the feed oxidizer gases in the tangentially-fired furnace which essentially depends on the location of the central vortex in this type of furnaces. This improvement on the combustion conditions can bring several benefits to the combustion characteristics and reduces the fouling and slagging problems on the surfaces of the heat exchanges. Regarding the cases investigated under full load operation, it can be seen that the flame temperature distributions of cases 2 and 5 showed a clear tendency toward the out-of-service burners. This feature might be caused due to the movement of the central vortex toward the turned off burners. A good distribution of the flame was achieved in cases 3 and 6 because of turning off the opposite burners. In panels (g) and (h), the flames are concentrated in the near-burner region due to the reduction in the mass flow rates of combustibles. Whereas the combustion flames are uniformly distributed in the burner and water wall regions for both cases 9 and 10 due to the higher aerodynamic effect of the PC and air adopted in these two cases.
4.2 Velocity distribution

Figure 3 presents the cross-section cuts of the gas velocity vector on the upper intermediate inert of the secondary air duct for the combustion cases (cases 1-6 as specified in Table 1) that work under full load operation. Connecting to Fig. 2, cases 3 and 6 showed a good flow field distribution in the furnace. In these two cases, the tangential distributions of the gas velocity vectors (central vortexes) were approximately close to the central zone of the furnace compared to the other combustion cases. As a result, this good tangential circulation of the gases led to improve the flame distribution, as seen in Fig. 2. In contrast, the central vortexes in cases 2 and 5 were away from the central position of the furnace and skew toward the furnace wall.
4.3 Species concentrations

Figure 4 a and b presents the distributions of mass fraction of CO$_2$ and CO respectively along the central line (X and Y = 0.0) of the furnace in the region of combustion zone (burner region) for different combustion cases: 2, 3, 5, 6, 9, and 10. Both figures show that there are two peak values for all combustion cases examined. The maximum values were firstly close to the main burners (PC burners), while the second max. values were in the inert burner region. These two values were resulted due to the availability of the high O$_2$ concentrations in these regions. In the case 6, the concentrations of CO$_2$ and CO were lower than those of the other combustion cases. As mentioned earlier, this improvement might be caused due to the good mixing condition adopted in this case.

Fig. 4. (a) Mass fraction (MF) of carbon dioxide for combustion cases (2, 3, 5, 6, 9, and 10) along the central line of the furnace in the burner regions; (b) Mass fraction of carbon monoxide for combustion cases (2, 3, 5, 6, 9, and 10) along the central line of the furnace in the burner regions.

5. Conclusion

A CFD model of a 550 MW tangentially-fired furnace at Loy Yang A power plant has been developed. The validated model was used to investigate the combustion characteristics and boiler performance under different firing conditions. The combustion scenarios of this work were based on the effect of the mass flow rates and distribution ratios for the PC and air in the combustion zone. Ten different combustion cases were investigated. The first six combustion cases were based on the change of the out-of-service burners under full load operation, while the rest cases were carried out at 20% lower and 20% higher than the standard operating conditions, as specified in Table 1. Temperature distributions, velocity distributions, and species concentrations are compared for all cases examined. The numerical results showed that both the cases 3 and 6 provide good flow field distributions and resulted in an improvement in the flame distribution in the furnace and water wall regions. A slight reduction in the CO$_2$ and CO concentrations was observed in the case 6 compared to the other combustion cases. This work may lead to optimize the operating conditions of the commercial tangentially-fired furnaces.

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