Seventh International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
9-11 December 2009

NUMERICAL MODELLING OF BROWN COAL COMBUSTION IN A TANGENTIALLY-FIRED FURNACE

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ABSTRACT

A CFD model of a 375 MW tangentially-fired furnace located in Australia's Latrobe Valley has been developed. Coal feed rates, air flow rates, coal particle size distribution and coal properties, obtained from plant data, are taken as input conditions in the CFD simulation. A level of confidence in the current CFD model has been established by carrying out a mesh independence test and comparing simulated results against power plant measurements. Performance of two turbulence models, standard k-ε model and SST model, are compared. The effect of particle dispersion on predicted results is found to be insignificant. The validated CFD model is then used to simulate several brown coal combustion cases at full load with different out-of-service firing groups.

INTRODUCTION

Brown coal has been the main energy source for steady economic development in Victoria, Australia (Li, 2004) for many years. About 97% of this brown coal is consumed by power stations in the Latrobe Valley region, producing over 85% of Victoria's electricity supply (Allardice, 2000). To better understand brown coal combustion in Latrobe Valley boilers, a Computational Fluid Dynamics (CFD) study has recently been conducted to investigate brown coal combustion in a 375MW tangentially fired furnace at the Yallourn W power plant, Latrobe Valley.

Early CFD modelling work on coal combustion in the 1980's (e.g. Boyd and Kent, 1986; Lockwood et al., 1988) mainly addressed preliminary model validation and demonstrated the potential of CFD models for coal combustion applications. In these studies, mesh densities were relatively low due to the limit of computing power and simple combustion models were used. Nevertheless, the CFD results showed reasonable agreement with plant measurements of gas velocity, temperature profile, and wall heat transfer. With advances in computing power, numerical algorithms and measurement instruments, more comprehensive validations of CFD results have been reported (for example; Fan et al., 1999; Zhou et al., 2002 and Zhou et al., 2009).

More recently CFD has been employed to study the performance of tangentially fired furnaces under different operating conditions, namely, burner out-of-service, coal blend and switch, particle size distribution, air and coal mass flow rates and, excess air ratio. Belosevic et al. (2006) carried out a numerical simulation of Serbian lignite combustion with different grinding fineness of coal and coal quality. The CFD results showed that fine particles burn rapidly, giving higher concentrations of CO_2 than those of coarse particles. Belosevic et al. (2008) numerically studied coal combustion under different operating conditions in a 350 MW tangentially fired boiler. Their model successfully predicted the influence of burner out-of-service, air/fuel ratio and boiler load, on the furnace process and operation characteristics. Spitz et al. (2008) simulated and analysed the influence of a sub-bituminous coal with high moisture content on performance of tangentially fired and opposite-wall utility boilers which were designed for bituminous coals. Backreedy et al. (2005) investigated the unburned carbon and NOx emission from a tangentially fired furnace using single coals and coal blends. They validated their model by comparing the simulation of a drop tube reactor with measurements and good agreement was achieved. For the tangentially-fired furnace, the temperature predictions and NOx concentrations compared well with measured values.

Another application of CFD is the prediction of NOx emission and flue ash emission from coal combustion (Bris et al., 2007; Diez et al., 2008; Choi and Kim, 2009 and many others). Other reported CFD simulations also cover particle ignition (Asotani et al., 2008), particle burnout (Chen et al., 1992), gas temperature deviation (Xu et al., 1998; Yin et al., 2003), and the reheater panel overheating problem (He et al., 2007). Generally, CFD has been found to be a feasible and powerful tool for studying pulverised coal combustion in tangentially fired furnaces.

This paper reports on recent progress made in the CFD simulation of the Yallourn W unit No. 3, which is a 375 MW tangentially fired furnace. Coal feed rates, air flow rates, coal particle size distribution and coal properties obtained from plant data are used as input conditions in the simulation. A level of confidence in the CFD model has been established by carrying out a mesh independence test and validating simulated results against power plant data. The impacts of turbulence models and particle dispersion on the CFD prediction are also investigated. The validated model is then used to simulate various combustion cases with different out-of-service firing groups.

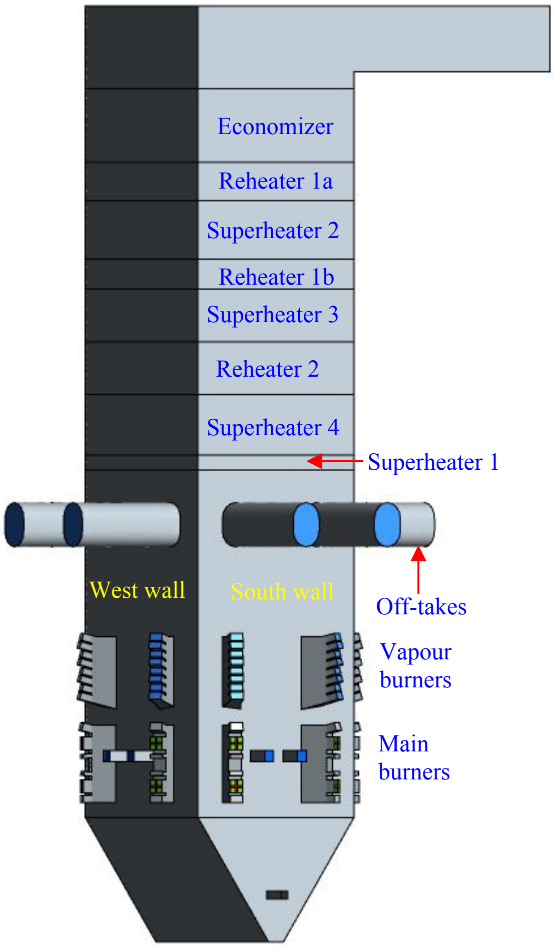


Figure 1: CFD geometry of Yallourn W unit No. 3

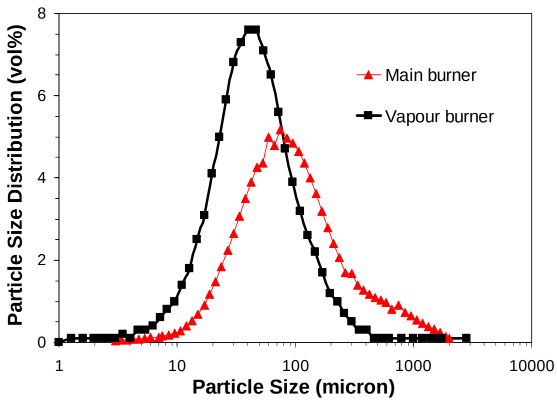


Figure 2: Mill coal particle size distribution at main and vapour burners.

MODEL DESCRIPTION

Boiler geometry and operating conditions

The Yallourn W unit No. 3 is 77.5m high and has a 15.9×15.9m² square cross-section. The unit generates 319kg-s⁻¹ of steam, at 16.8MPa and 541°C when operating at maximum continuous rate (MCR) operation. Geometry of the CFD model for the boiler is shown in Figure 1, and includes part of the upstream burner ducts and extends up to the exit of the economizer . This furnace is equipped with eight firing groups. Each firing group is comprised of two wall-mounted slot main burners (upper and lower), two vapour burners (upper and lower), mill and duct system, and a gas off-take that extracts hot furnace gas to heat and dry the raw brown coal in the mill. The raw brown coal is put in the duct system without any pre-drying process and ground by the mills to give a fine particle size. The coal is dried, by hot furnace gas recycled from the off-takes, in the mill system before being fed into the furnace through the vapour and main burners. Typical coal size distributions of the pulverised brown coal at vapour burners and main burners are shown in Figure 2. Properties of the high moisture content raw brown coal are given in Table 1.

Table 1: Raw brown coal properties.

Proximate analysis	(db w%)
Fixed carbon	47.2
Volatile matter	51.3
Ash	1.5
Ultimate analysis	**(daf w%)**
C	66.44
H	4.5
N	0.57
S	0.19
O	28.3
Moisture (w%)	66
Gross dry specific energy ($MJ.kg^{-1}$)	25.1

Table 2: Heat sink values for convective tube banks.

Heat Exchanger	Heat sink value (MW)
Superheater 1	76.1
Superheater 2	77.6
Superheater 3	145.2
Superheater 4	80.2
Reheater 1a	25.6
Reheater 1b	40.7
Reheater 2	114.2
Economizer	77.8

At the MCR operation six firing groups are normally required to supply 145 $kg\text{-}s^{-1}$ of raw brown coal particles through corresponding vapour and main burners to the furnace. Hence two firing groups are out-of-service with no coal flow. About 20 $kg\text{-}s^{-1}$ of air flows through each of the out-of-service firing groups protecting the burners from a large amount of radiant heat from combustion in the furnace. In plant operation selection of the two out-of-service firing groups is normally determined by the maintenance requirements. Total secondary air flow under the MCR operation is about 388$kg\text{-}s^{-1}$, which is supplied through the secondary air nozzles. These secondary air nozzles are located in the main burners just above and below the primary nozzles through which the gas and pulverised coal enters the furnace. In this study, the coal flow rate, air flow rate and furnace gas flow rate are assumed to be evenly distributed to the six in-service firing groups.

Detailed geometry for tubes in the convective passes has not been included in the current CFD model, since the main focus of the current study is on coal combustion and heat transfer in the radiant pass of the furnace. However, the regions where convective tube banks are located has source terms added to the momentum and energy equations. The source terms account for the tubes by damping the streamwise velocity components and generating a pressure drop as a function of gas phase velocity. Heat absorption in the convective tube banks is also included via a source term as given in Table 2. These values are based on plant measurements.

Gas phase and particle phase models

A commercial CFD code, ANSYS/CFX 12.0 (2009) has been applied to predict the pulverised coal combustion process. The coal combustion process is modelled by the following reactions:

$$\text{Coal} \rightarrow \text{Volatiles} + O_2 \quad (1)$$

$$\text{Volatiles(HC)} + O_2 \rightarrow CO + H_2O \quad (2)$$

$$C(\text{char}) + \frac{1}{2}O_2 \rightarrow CO \quad (3)$$

$$CO + \frac{1}{2}O_2 = CO_2 \quad (4)$$

The gas phase flow in the furnace is taken as a gas mixture consisting of all the gaseous components including O_2, H_2O, CO_2, CO, N_2, NO and volatiles. These components are assumed to mix at the molecular level, sharing the same mean velocity, pressure and temperature fields (ANSYS/CFX, 2009). Bulk motion of the gas mixture is modelled using single velocity, pressure, temperature and turbulence fields. Turbulence is modelled by the most widely used standard k-ε model. Performance of the SST model is also evaluated and compared with the standard k-ε model. Thermal radiation through the gas phase is modelled using a discrete transfer model.

Temperature, composition and velocity of coal particles along their trajectories are predicted using a Lagrangian particle tracking model. The Lagrangian method determines the trajectory of a discrete particle by integrating the force balance on the particle. Appropriate forces such as the drag, gravity and turbulent dispersion forces have been considered in the equation of motion for this work. The calculation also takes into account the interactions between the gas and particle mass, momentum and energy with full-coupling employed between the phases.

Turbulent dispersion of particles is handled by integrating the trajectory equations for representative particles using the instantaneous fluid velocity along the particle path during the integration process. A stochastic method is utilized in which 7,100 sample coal particle are injected through each firing group, make a total of 42,600 sample coal particles tracked in the furnace.

The single first order reaction (SFOR) model is used to calculate the devolatilisation rate of coal particles. The pre-exponential factor and activation temperature for the model in this study are taken from Duong (1987). The global reaction model is used to calculate the coal char oxidation. The pre-exponential factor and activation temperature of the char oxidation model are 497 $kg.m^{-2}.s$ and 8540K (Wall et al., 1976), respectively.

The mass, momentum, chemical species and energy equations are discretised using the finite volume approach. The discretised gas continuity and momentum equations are solved in a fully coupled manner. The convergence criterion for gas phase properties is 10^{-5} for the RMS residuals. Further details regarding the fluid flow, turbulence models, radiation models, heat transfer models, and coal combustion models along with validation for a pilot-scale furnace can be found in Tian et al. (2009a).

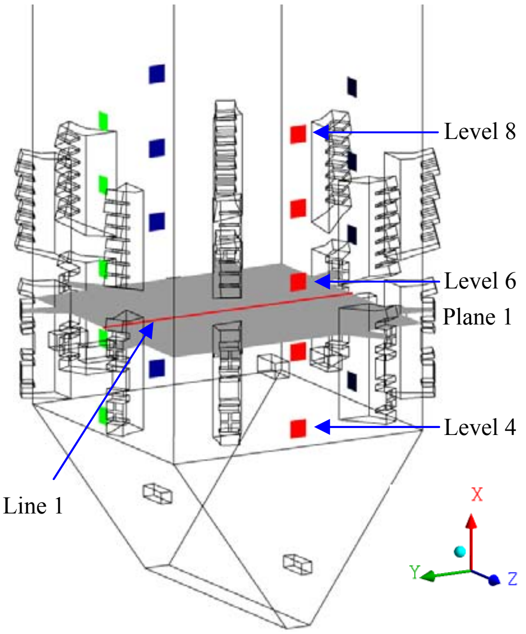


Figure 3: Locations of ports, line 1 and plane 1.

RESULTS AND DISCUSSIONS

Operation of unit 3 at Yallourn W power station normally requires six firing groups at full load (MCR condition). The other two mills are switched off and only cooling air flows through the burners. This burner out-of-service technique helps to decrease the local air-to-fuel ratio at the exit locations of in-service burners, leading to reduced furnace temperature and lower NOx emission. A series of 5 studies have been conducted to simulate coal combustion in the furnace with different firing groups switching off at MCR condition. Selected results of cases 1-5 (specified in Table 3) are presented and discussed in this paper. The locations of firing groups and the predicted velocity vectors on plane 1 (shown in Figure 3) for case 1 are shown in Figure 4.

Table 3: CFD simulated cases at MCR conditions.

Case number	1	2	3	4	5
Out-of-service burners	2, 6	3, 6	4, 6	5, 6	6, 7

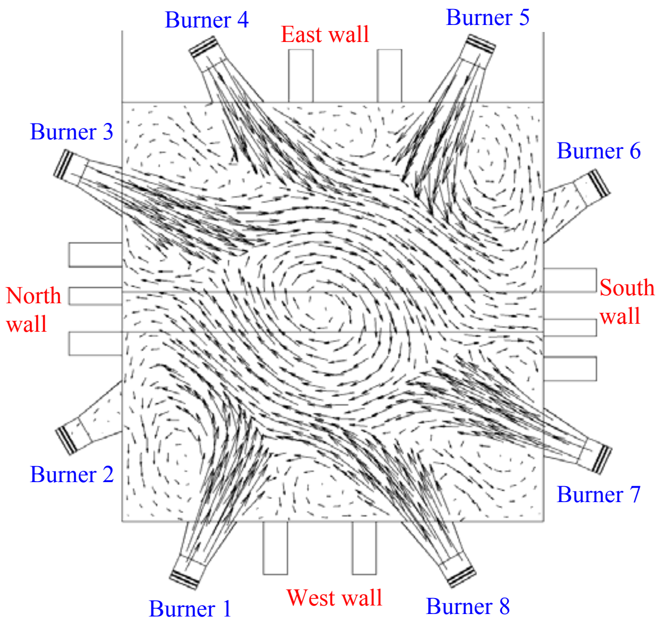
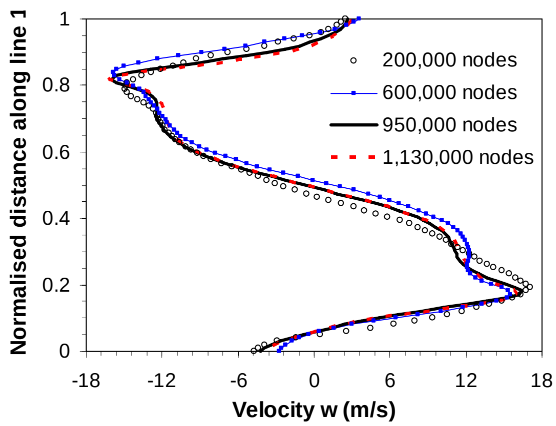


Figure 4: Location of burners and predicted gas velocity vectors for case 1 on plane 1.

Grid independence test and Validation

Pulverised coal particle combustion in a particular furnace is a complex phenomenon and is determined by the furnace type, furnace geometry, coal properties, operational conditions, etc. Previously validation of the coal combustion and turbulence models has been conducted for a non-swirling coal flame in a pilot-scale furnace (Tian et al., 2009a). Tian et al., 2009b has recently presented validation of isothermal gas-particle jets in crossflow. The gas-particle jets in crossflow geometry and conditions are representative of the air-coal particle flow through burners in the tangentially fired furnace. In both validation exercises, the CFD models used in the current study provide predictions in good agreement with the detailed measurement available in literature. Nevertheless, due to the complexity of both the physical process and the combustion model, a three-step validation procedure is implemented to ensure the reliability of predictions in this CFD model. This procedure includes: 1) a mesh independence test, 2) comparison of predicted wall incident heat flux profiles with power plant measurements, and 3) comparison of predicted flue gas exit temperature (FGET) before air heaters, gas component concentrations in flue gas and total boiler heat supply against measurements taken in the boiler.

A mesh independence test is conducted for case 1 where firing groups 2 & 6 are switched off. An initial mesh with about 200,000 nodes has been created in the computational domain. The mesh is then refined progressively, resulting in finer meshes with 600,000, 950,000 and 1,130,000 nodes. Mesh independence is checked by comparing the gas phase velocity component w along z-axis and the gas temperature along line 1 in the furnace (the red line shown in Figure 3). Figure 5a shows the comparison of gas velocity w and Figure 5b gives the comparison of temperature profiles based on the four mesh densities. The fine mesh (1,130,000 nodes) and medium density mesh (950,000 nodes) yield similar results. Therefore, the mesh density of 950,000 nodes is applied for further work reported in this study.



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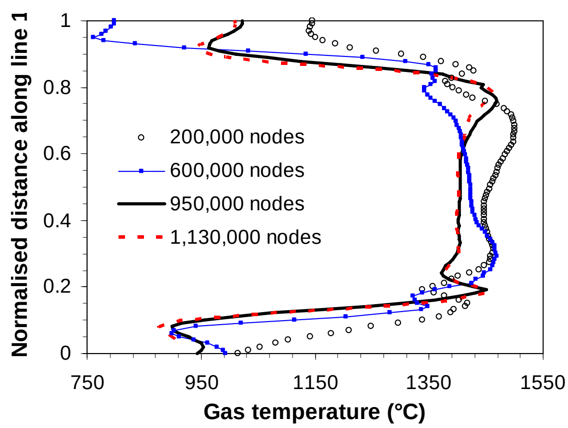


(b)

Figure 5: Mesh independence test based on (a) gas velocity w, (b) gas temperature along line 1, case 1.

A comparison of predicted wall incident heat flux profiles for case 3 with measurements (HRL, 2005) is shown in Figure 6. At the time of measuring, the operating conditions of the unit were the same as those of case 3; the unit was operating at the design MCR and burners 4 & 6 were out-of-service. Both measurement and prediction of wall heat fluxes were taken through ports in the furnace walls. The heat flux for each level was the average of the ports in all four walls for that level. Locations of the ports for the CFD calculation are displayed in Figure 3. The CFD model performs well; the trend of the heat flux on the walls is successfully captured and good agreement is obtained between the measurement and simulation. In both measurements and predictions, high wall incident heat fluxes are found at levels 4, 5, and 6, which are the location of the main burners and lower vapor burners. This indicates that most of the combustion occurs at the burner level and is consistent with the design concept.

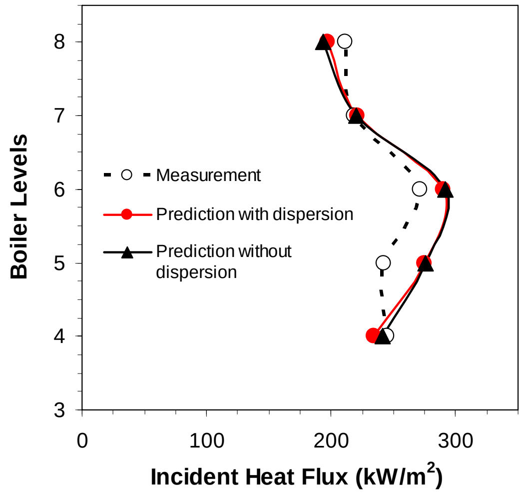


Figure 6: Comparison of calculated and measured wall incident heat flux profiles, burner 4&6 off at MCR. (Measurements from HRL, 2005)

Predicted flue gas exit temperature (FGET), flue gas temperature before air heaters, gas component concentrations in flue gas, and total boiler heat supply has been compared against measurements taken in the boiler for case 2, i.e. firing groups 3&6 out of service. Validation of the FGET and total boiler heat supply are carried out using power plant instrument measurements gathered at Yallourn W power plant during November 2006. Measurements of flue gas components (O_2, CO_2, H_2O concentrations) and flue gas temperature before air heaters are obtained from HRL report (2004). As shown in Table 4, CFD predictions are in good agreement with the measured data.

	Measurement	k-ε	SST
FGET (C°)	1000-1175	1087	1090
Flue gas temperature before air heaters (C°)	382-402	394	400
Flue gas O_2 (w%)	3.7	3.98	3.74
Flue gas CO_2 (w%)	18	19.3	19.7
Flue gas H_2O (w%)	20	18.8	18.9
Total heat supply (MW)	899	911	914

Table 4: Measured and calculated FGET, flue gas temperature before air heaters, flue gas components and total boiler heat supply, case 2.

Generally, a level of confidence in the current CFD models has been established by the mesh independence test and validation against power plant data, combined with the previous validation reported elsewhere (Tian et al., 2009a and b).

Turbulence Models and Particle Dispersion

In a preliminary study (Tian et al., 2009a), six two-equation RANS models were used to simulate a non-swirling coal flame in a pilot-scale furnace. For that case predictions of the standard k-ε model, RNG k-ε model, BSL and SST models were generally in good agreement with the experimental data. Predictions using the SST and BSL models were almost identical, while results of the standard k-ε model and RNG k-ε model were also very close. The standard k-ε model and SST model were further compared in Tian et al. (2009b) where gas-particle flow in three inclined rectangular jets in crossflow was simulated. The gas phase predictions were validated against laser measurements of the gas phase velocity profiles along the centre plane of the primary jet and secondary jet. Gas and particle flows predicted by both models are in reasonable agreement with the detailed experimental data, although the SST model showed a slightly better agreement with the measurements than the standard k-ε model.

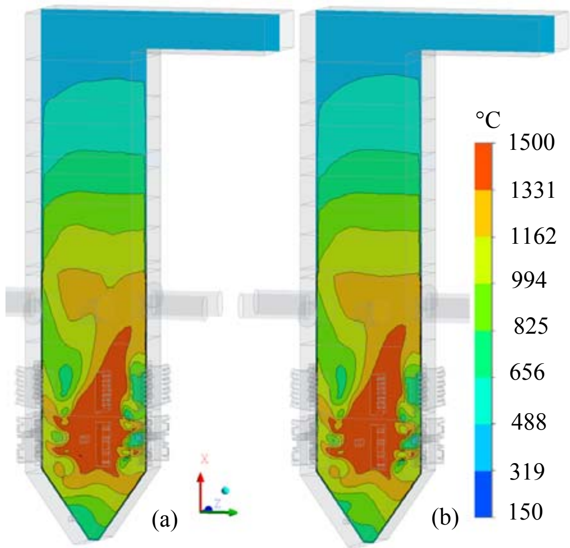


Figure 7: Predicted gas temperature profiles of mid-plane: (a) standard k-ε model, (b) SST model, case 2.

As shown in Table 4, predictions of FGET, flue gas temperature before heaters, flue gas concentration, and total boiler heat supply based on the standard k-ε model and SST model are quite similar. A comparison of the gas temperature contours on the mid plane of the furnace calculated by both turbulence models is shown in Figure 7. It is clearly seen that the difference between the simulated temperature profiles based on the two models is small.

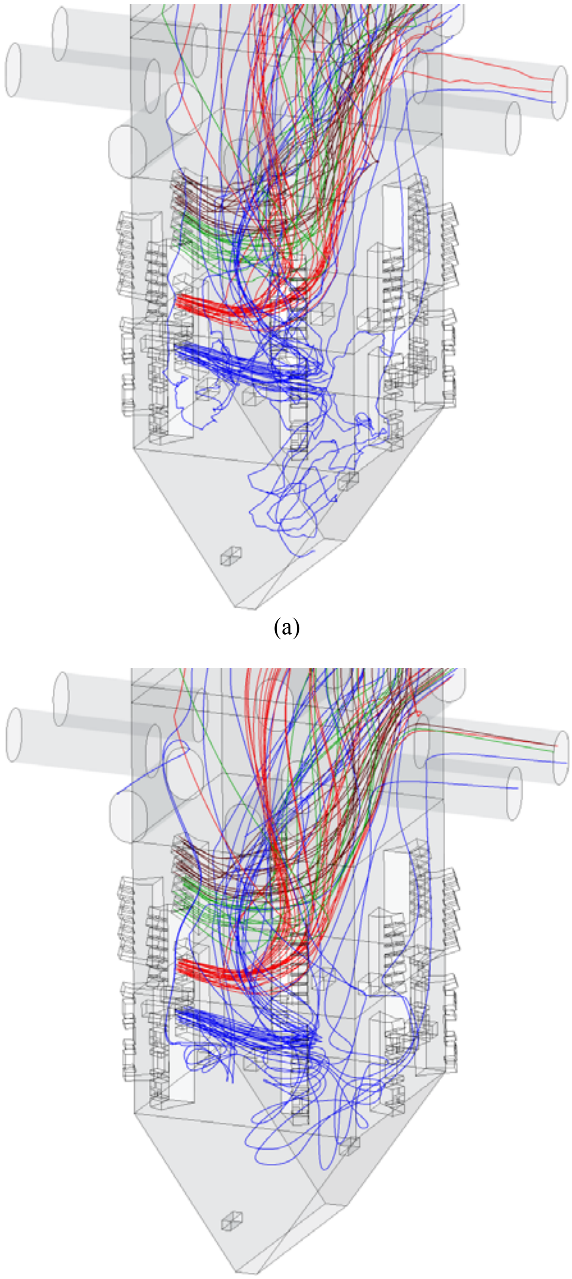
Turbulent dispersion of particles is handled by a stochastic method. Truelove (1986) studied the influence of particle dispersion on the CFD prediction of coal combustion in a swirling coal flame. It was found that for a type 2 flame, the effect of particle dispersion became increasingly more significant the lower the volatile content of the coal. The effect of particle dispersion on the prediction of the combustion of Latrobe Valley brown coal in the furnace is investigated here and is found to be small. For example, the predicted wall incident heat fluxes of case 3 with/without particle dispersion force are illustrated in Figure 6. The difference between the predicted heat fluxes with/without particle dispersion force is negligible. The predicted particle trajectories from firing group 5 of case 3 with particle dispersion are shown in Figure 8a, while the trajectories without particle dispersion are shown in Figure 8b. Many particles from the lower main burner (with blue color) circulate at the center of the furnace following the centre vortex that is formed by the gas and particle jets. Particles from the vapor burners flow out of the furnace and into the convective pass without interacting with the centre vortex. The trend of non-dispersed particle trajectories is very similar to that of dispersed particle trajectories, though they are not coincident. Some dispersed particles from the lower main burner travel into the ash hopper further than the non-dispersion case. This may explain the slightly smaller heat flux with particle dispersion than that of without particle dispersion case at level 4 in Figure 6.

Case number	1	2	3	4	5
FGET (C°)	1091	1087	1086	1098	1085
Flue gas temperature before air heaters(C°)	410	394	402	398	381
Flue gas O_2 (%)	3.6	3.98	3.58	3.5	3.66
Flue gas CO_2 (%)	19.8	19.3	19.9	20	19.7
Flue gas H_2O (%)	19.4	18.8	19.1	18.7	19.1
Total heat supply (MW)	907	911	926	939	942

Table 5: Measured and calculated FGET, flue gas temperature before air heaters, flue gas components and total boiler heat supply for different out-of-service cases.

Cases with different out-of-service firing groups

Figure 9 shows the 1327 °C temperature iso-surface for each of the 5 cases. It is clearly evident that the high temperature zone is at the centre of the furnace in the case of firing groups 2&6 off (Figure 9a). As shown in Figure 4, the injected coal particles and gas from the burners form a large swirl or vortex at the furnace centre for case 1. This large vortex is an inherent design feature of tangentially fired furnace aimed to enhance mixing in the furnace. The high temperature zone and the centre vortex of case 1 are symmetric. The high temperature zone skews towards the out-of-service burners for the other cases, as shown in Figure 9 b-e, the asymmetry is especially evident for case 4 where burners 5&6 off. One possible cause of this phenomenon is the relatively high oxygen in the out-of-service burner exits, which arises because about 20kg-s^{-1} of cooling air flow and no fuel flows through the out-of-service burners. Model results indicate that the large vortex transports unburnt volatiles and coal particles from upstream in these oxygen rich zones where they combust. Furthermore, the cooling effect is significantly weaker in the out-of-service burners than the in-service burners.



(a)

(b)

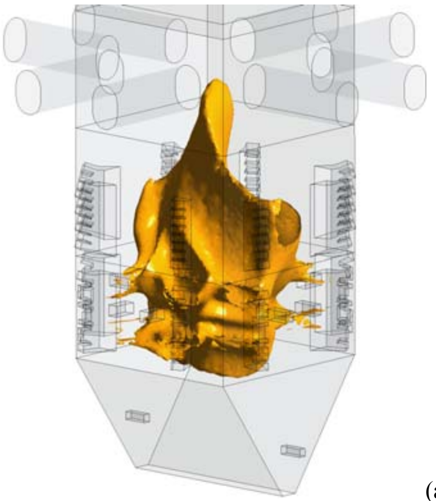
Figure 8: Predicted particle trajectories of case 3: (a) with particle dispersion, (b) without particle dispersion.

Table 5 lists the predicted boiler parameters for the different cases. Boiler performance for each of the different cases is similar. The total heat supply of case 4 and case 5 are slightly higher than the other cases. The furnace is considered to be in a ‘clean condition’ in this study, i.e. the furnace heat transfer surfaces are clean and there is no slagging on the furnace water tube walls. The locally high temperature of case 4 and case 5 are quite likely to result in severe local slagging problems if the boiler were to be operating in this configuration for an extended length of time.

CONCLUSIONS AND FUTURE WORK

A CFD model of a 375 MW tangentially fired furnace at Yallourn W power plant has been developed. A substantial amount of work has been undertaken to validate the CFD model against measured operating data and to gain an understanding of the sensitivity of CFD results to modelling parameters. To this end two turbulence models, the standard k-ε model and SST model, are used to model gas phase turbulence. Both turbulence models provide similar predictions that are in good agreement with the plant data. The effect of the particle dispersion on the CFD prediction is found to be insignificant. This is consistent with the observation of Truelove (1986) who found the particle dispersion has little effect on the high-volatile coal combustion.

This validated model is then employed to investigate brown coal combustion at full load with various firing groups out-of-service. It is found that the values of total boiler heat supply for case 4 and case 5 are slightly higher than those of other cases. However, the high temperature zones of these two cases are closer to the walls than for other out-of-service burner configurations. This higher temperature may lead to severe slagging problems on the wall.



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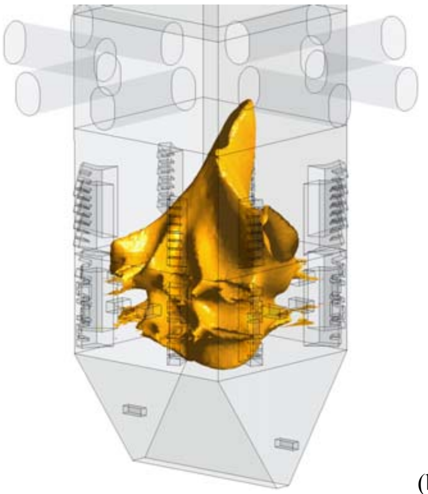

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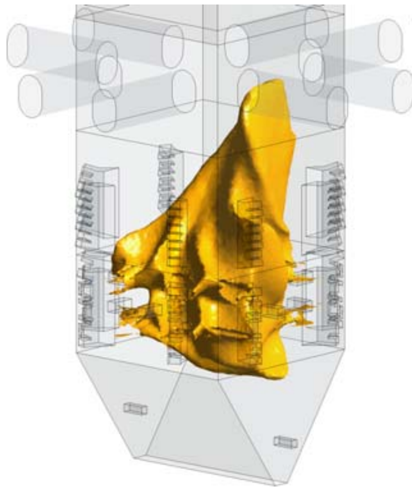

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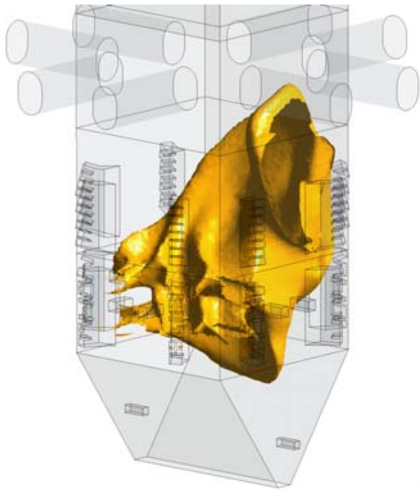

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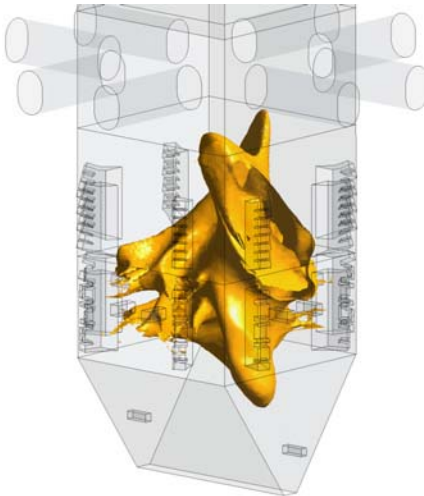

(e)

Figure 9: Iso-surfaces at 1327 °C: (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5.

ACKNOWLEDGMENTS

The financial support provided by the Victorian Government Department of Primary Industries under the ETIS Program is gratefully acknowledged. The authors also thank Steve Pascoe and Yorrick Nicolson of Yallourn W power plant for providing plant data for the CFD simulation and discussion about the predicted results.

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