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Modelling of Coal Combustion in Full-Scale Industrial Furnace

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Abstract
A Computational Fluid Dynamics (CFD) model for simulating fluid flow and combustion in industrial scale tangentially brown-coal fired German Furnace (600MW) is presented in this paper. The CFX Package (CFX4, 1997) has been used to model this furnace. It consists of Standard k-epsilon turbulence model for fluid flow, Shah's Discrete transfer Model for radiation, Single-reaction Devolatilization model for devolatilization, Eddy-break-up model for gaseous combustion, Field's Model for Char oxidation. The predicted velocity and temperatures have been validated against the available measured data. Reasonably good agreement between the predicted results and the measured data was obtained.

Introduction
Brown Coal is one of the cheapest fuels and is available in sufficient quantities in Australia. Because of the cheap price of coal, so far much attention was not paid to improve the efficiency of brown-coal fired furnaces. However, the new restrictions on generating "clean" energy have encouraged the designers to design more efficient devices. It is estimated that the overall efficiency of the coal consuming power plants on an average is only about 18%. There is therefore, much scope to improve the efficiency of such equipment. CFD Modelling has shown to be an efficient way for modelling pulverized coal combustion systems (Magel et al., 1995; Stanmore et al., 1998). The recent development in computer hardware and numerical methods leads to the possibility of use more complex combustion models in three-dimensional predictions of utility boilers. This paper is a preliminary study adopted for validating the CFD coal combustion methodology for full-scale brown-coal furnace. The results obtained are validated against the available measured data and the numerical predictions obtained with AIOLOS (Magel et al., 1995). AIOLOS is a CFD package developed and used at Stuttgart University, Germany.

Physical Models
In modelling the coal combustion process, the numerical simulation of gas conditions within the furnace is accomplished by coupling the fluid dynamics relationships with sub-models that predict heat transfer (conduction, convection and radiation), turbulence, coal particle trajectories and temperatures, coal devolatilization, char combustion and equilibrium chemistry. The different sub-models form strongly coupled set of partial differential equations. Each of these equations, except the one for radiation, can be written in form of a general transport equation:

$$\frac{\partial}{\partial x}\left(\rho u \Phi\right) = \frac{\partial}{\partial x}\left(\Gamma \frac{\partial \Phi}{\partial x}\right) + S_{\Phi} \qquad (1)$$

where ρ u and Γ are the density, velocity and the diffusion coefficients. This equation describes the local change of the variable Φ due to convection, diffusion and production under steady state conditions. Depending on Φ, the above equation represents mass, momentum, species, or energy conservation. In case of non-isothermal conditions the variables Φ are Favre-averaged.

Coal Combustion Scheme
Coal combustion is a very complex process and not all-physical aspects are well-understood (Magel et al., 1995). The combustion of a coal particle is a three stage process: drying and devolatilization of the raw coal particle followed by the oxidation of the residual char to leave incombustible ash (Field et al., 1967; Badzioch & Howksley, 1970).

Coal Devolatilization
The coal is considered to have fixed fractions of volatiles, char and ash. The rate of production of the volatile gases is given by the first order reaction:

$$\frac{dV}{dt} = k_V \left(V_f - V\right) \qquad (2)$$

where V is the mass of volatiles which have already evolved from unit mass of raw coal, and V_f is the final yield of the volatiles. The rate constant k_v is expressed in Arrhenius form as;

$$k_V = A_V \, exp\left(-\frac{E_V}{RT_P}\right) \qquad (3)$$

where T_p is the temperature of coal particle (assumed uniform), and A_v and E_v are constants, determined experimentally for the particular coal. And R is the universal gas constant.

Gaseous Combustion of Volatile Yield
In a fast chemical reaction model, it is assumed that if fuel and oxidant are simultaneously present at the same point then an instantaneous reaction occurs producing combustion products. Fuel and oxidant are assumed to combine in a fixed ratio i, the stoichiometric ratio, such that:

1 *kg* fuel + i *kg* oxidant -> (1 + i)*kg* products.

The mixture fraction f for the reaction can be defined by

$$f = \frac{\chi - \chi_0}{\chi_F - \chi_0} \qquad \text{where} \quad \chi = m_F - \frac{m_0}{i}, \quad (4)$$

where, m is the mass fraction and subscripts F and O refer to fuel and oxidant respectively. So the χ_0 and χ_F used in above equation are $\chi_0 = -\frac{1}{i}$ and $\chi_F = 1$.

The mean F of f satisfies a conservative transport equation of the form

$$\frac{\partial \rho F}{\partial t} + \nabla.(\rho \mathbf{U} F) - \nabla.\left(\left(\frac{\mu_T}{\sigma_T} + \frac{\mu}{\sigma_L}\right)\nabla F\right) = 0 \qquad (5)$$

Here ρ is the fluid density, **U** is the mean fluid velocity, μ and μ_T are molecular and turbulent fluid viscosity and σ_L and σ_T are equivalent Prandtl numbers.

By definition, f is always positive and attains its stoichiometric value F_{st} when χ =0.

Thus $$F_{ST} = \frac{1}{1+i}$$

Eddy-Break-Up (EBU) Model

This model, first proposed by Spalding (1972) and modified by Magnussen (1989), is based on the turbulence decay and assumes infinite-fast-chemistry.

In CFX-4, for the Eddy-break-up model an explicit equation is solved for the mass fraction of fuel:

$$\frac{\partial \rho m_F}{\partial t} + \nabla.\left(\rho U m_F\right) - \nabla.\left(\left(\frac{\mu_T}{\sigma_T} + \frac{\mu}{\sigma_L}\right)\nabla m_F\right) = -\rho \frac{\varepsilon}{k} C_R C_A M_{\lim} \quad (6)$$

In CFX-4 the terms C_R, C_A and M_{lim} are modelled as:

$$C_R = \begin{cases} 23.6\left(\frac{\mu\varepsilon}{\rho k^2}\right)^{\frac{1}{4}}, & \text{viscous mixing model} \\ 4.0, & \text{collision mixing model} \end{cases}$$

$$C_A = \begin{cases} 1.0, & \text{infinite rate chemistry} \\ 1.0, & \mathrm{D} \geq \mathrm{D_{ie}} \quad \text{finite rate chemistry} \\ 0.0, & \mathrm{D}\ \pi\ \mathrm{D_{ie}} \quad \text{finite rate chemistry} \end{cases}$$

D is the DamkÖhler number. It is defined by

$$D \equiv \frac{\tau_e}{\tau_{CH}}$$

where $\tau_e \equiv \frac{k}{\varepsilon}$ and τ_{CH} is the chemical induction time.

The mass fractions for oxidant and product are defined as follows:

$$m_O = 1 - m_F - \frac{F - m_F}{F_{ST}} - m_{PC} \quad \text{and}$$

$$m_P = 1 - m_F - m_O - m_{PC}$$

where, m_{PC} is the mass fraction of the char products.

Char Oxidation

Field *et al* (1967)proposed a char burnout model based on a global reaction of order unity. In the Field Model, a char particle is considered to be a spherical particle surrounded by a stagnant boundary layer through which oxygen must diffuse before it reacts with the char. The oxidation rate of the char is calculated on the assumption that the process is limited by the diffusion of oxygen to the external surface of the char particle and the effective char reactivity. The rate of diffusion of oxygen is given by $K_d(P_g\text{-}P_s)$, where P_g is the partial pressure of oxygen in the furnace gases far from the particle boundary layer and P_s is the oxygen pressure at the particle surface. The value of K_d is

$$k_d = \frac{2.53X10^{-7}}{R_P}\left(\frac{T_P + T_g}{2}\right)^{0.75}\frac{P_A}{P} \quad (7)$$

where R_p is the particle radius, T_p is the particle temperature and T_p is the far-field gas temperature. Further, P is the local pressure and P_A is atmospheric pressure. The char oxidation rate per unit area of particle surface is given by K_cP_s. The chemical rate co-efficient k_c is

$$k_c = A_c T_P \exp\left(-\frac{T_c}{T_P}\right) \quad (8)$$

where the parameters A_c and T_c depend on the type of coal, and are specified as input parameters. In CFX-4 the recommended values for A_c and T_c are 497 kg/m2/atm/s and 8540 K (Wall et al, 1986). The overall char reaction rate of a particle is given by:

$$\left(k_d^{-1} + k_c^{-1}\right)^{-1} P_g\, 4\pi R_P^2 \frac{P}{P_A} \quad (9)$$

and is controlled by the smaller of the rates k_d and k_c.

Model Description

The furnace is tangentially fired with 16 burners in two levels with 8 pairs of vertically arranged burners. Each of them is corresponding to one mill. The model is on the basis of 7 out of 8 mills are operational, which is the usual practice in the power plant to keep one mill on standby. In setting the various sub-models for this study, the following consistency has been maintained with AIOLOS (Magel et al., 1995):

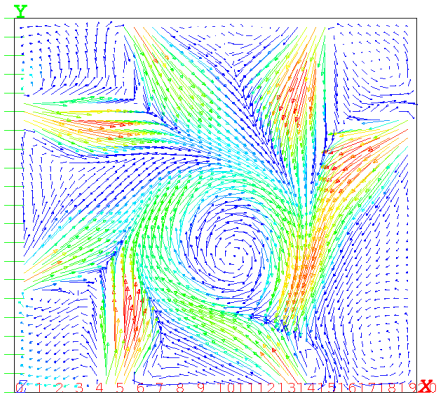
SUB-MODELS	AIOLOS	CFX-4
Coal Devolatilization	Single Reaction Devolatilization	Single Reaction Devolatilization
Gaseous Combustion	Eddy-dissipation-concept (EDC)	Eddy-Break-Up (EBU)
Char burnout	Global Reaction (Field model)	Global Reaction (Field model)
Radiation	Shah Model	Shah Model
Turbulence equations	Standard k-epsilon	Standard k-epsilon

Table 1. Comparison of sub-models used

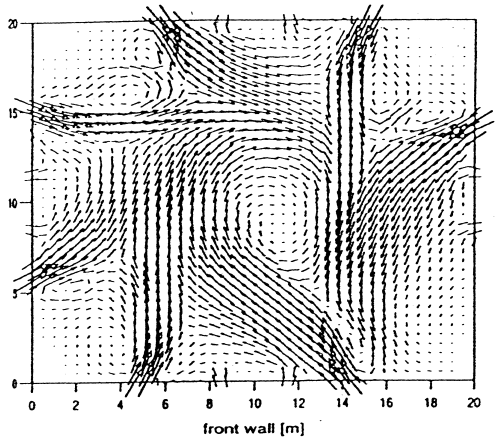
The above table shows that all the sub-models are similar in two codes except for Gaseous Combustion. AIOLOS has used Eddy-dissipation-concept, which is an extended form of Eddy-break-up model. The basic difference is that AIOLOS considers 'finite rate chemistry' whereas fast chemistry assumption is assumed sin the present study.

Results and Discussion

The results obtained using CFX-4 have been compared with the predicted results of AIOLOS (Magel et al., 1995) and validated against the measured data (Magel et al., 1995). Comparing Fig.1 (a) with Fig.1 (b) it is evident that the flow pattern predicted at lower burner level by CFX is same as that of AIOLOS. There is no flow at the right-bottom corner of Fig.1 (a & b), this is because of the fact that the burner at that position was not operational. Furnace has been modelled with 7 burners in operation to keep the similarity with the real life furnace used in (Magel et al., 1995). The predicted flow pattern shows a central vortex and recirculation at the corners (Fig.1a).



CFX (a)



AIOLOS (b)

Fig. 1: Comparison between CFX (a) and AIOLOS (b) predicted velocity vectors at Lower burner level (31.9 m).

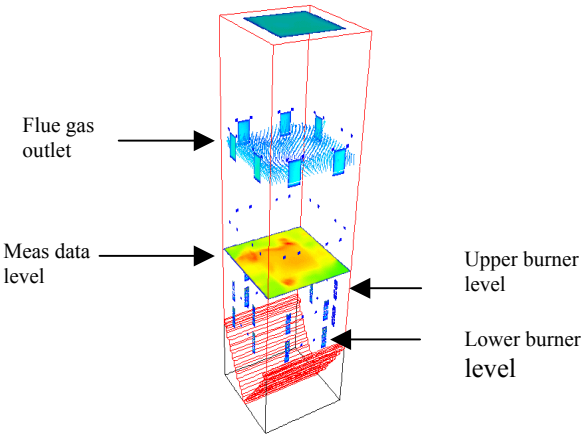


Fig.2: Inlet and Outlet Patches of NDAH (NIEDERAUSSEM H) Furnace

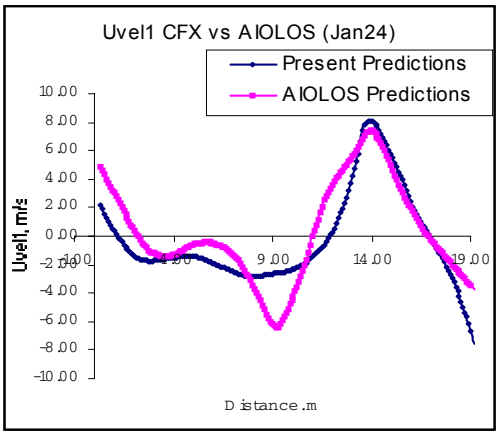


Fig.3: Comparison of U velocity Profile at lower burner level (31.9 m) predicted by AIOLOS and CFX-4

Fig.1 (a) shows the position of the level for which AIOLOS predicted and measured data are available. For this position the velocity, temperature and CO_2 profiles have been plotted in Fig. 3, 4 &5.

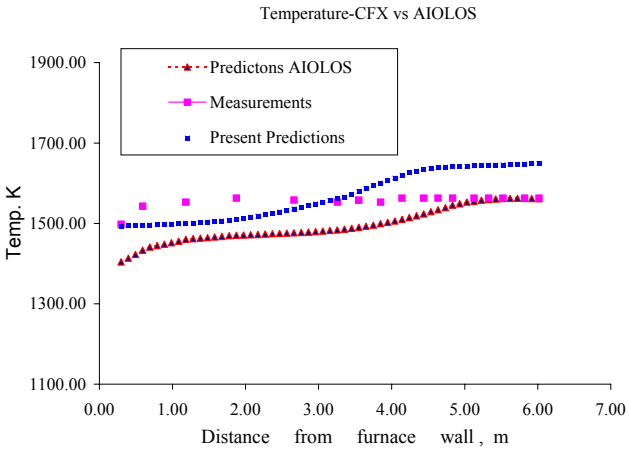


Fig.4: Comparison between Measurement and Predicted Temperature Profile

Fig.3 shows the velocity component along Y-axis (Fig.1a) at a distance of 2.0 m from the furnace wall. This plot is on the side where one burner was shutdown. This is the reason why the velocity at a distance of 5.0m along the Y-axis is the lowest. At a distance of 9.5 m along Y-axis, the present simulation underpredicts U velocity as compared to that of AIOLOS. Since there is no measured data for velocity, it is not possible to comment on the accuracy of the velocity prediction.

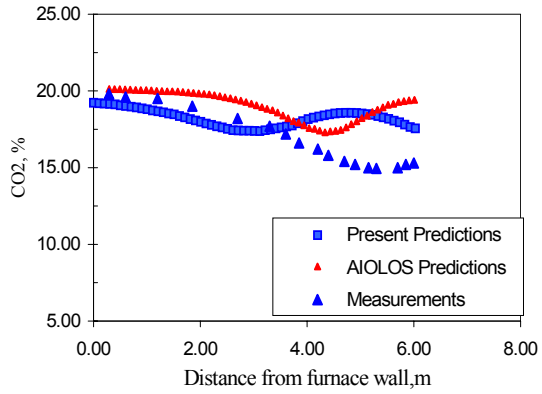


Fig.5: Predicted and measured CO_2 by AIOLOS and CFX

Fig.4 shows a reasonable agreement among present predictions, AIOLOS results and measured temperature datas upto a distance of 6m from the furnace wall. However the present prediction has over-predicted temperature after 3.5m from the wall. This over prediction is small and is around 3.5%. Fig. 5 shows the comparison of CO_2 values between predicted and measured data. Upto to a distance of 3.8m there is good agreement among them. The difference beyond that region could be attributed to the highly unstable flame condition, which influences the chemical reaction, hence the amount of CO_2 concentration. At a distance of 6.0m from the wall, current predictions are closer to the measured value compared to AIOLOS predictions. The over-predictions in this study may be attributed to the fact that all the volatiles and char has been considered to be completely converted to CO_2, but in reality there is always some CO with CO_2.

Conclusions

A generalized, three-dimensional combustion model has been presented which can be used to simulate full-scale industrial furnace. The model is compared with an existing CFD model and available experimental data and reasonably good agreement was obtained

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