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CFD MODELLING OF PULVERIZED COAL COMBUSTION IN A ROTARY LIME KILN

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ABSTRACT

Computational fluid dynamics (CFD) has been used to investigate the combustion processes occurring within a large-scale rotary lime kiln. Numerical results were validated against experimental data from the International Flame Research Foundation's (IFRF) Furnace No.1. The validation study focussed on comparisons between the finite rate and mixture fraction/PDF approaches to combustion chemistry, and different methods for defining coal particle size distributions. The aerodynamics and effects of varying the coal flow rate have been investigated for the rotary lime kiln. In this preliminary study and because the main interest is the flame characteristics, the effects of the reacting limestone bed have been ignored. The findings of the CFD investigation will help improve the economic and environmental impacts of rotary lime kilns. The studies also lay the foundations for future investigations into a hybrid, pulverised coal and waste oil, fuel system for rotary kilns.

INTRODUCTION

As global warming continues to impact the environment within which we live, the burning of fossil fuels as a source of energy is being placed under increased political and social scrutiny. As a result, industrial users of coal are being forced to either scale back consumption, or find ways to reduce total CO_2 emissions, while maintaining current production rates. Concurrently, with the globally increasing price of coal and focus on refuse recycling there is a move towards firing waste products, particularly biomass and waste oil, as a substitute for common fossil fuels such as coal.

McDonald's Lime in Otorohanga, New Zealand operate two pulverised coal fired, rotary lime kilns producing burnt and hydrated lime for a variety of customer bases including the gold, steel, roading and water treatment industries. Each kiln uses approximately 100 tonnes of coal per day producing in excess of 400 tonnes of carbon dioxide. The decomposition of limestone in each kiln releases carbon dioxide at an even greater rate. McDonald's Lime have turned to numerical modelling as a way to improve the environmental and economical aspects of their production processes.

Numerical methods such as Computational Fluid Dynamics (CFD) allow the testing of many variable combustion parameters that are either impossible to test on full-scale equipment, or time consuming, expensive and inaccurate with small-scale experiments. CFD has gained widespread recognition as a useful tool for studying pulverised coal flames, especially for bitumous coals (Bosoaga et al., 2006). The use of CFD allows the analysis of a system involving heat transfer, fluid flow, combustion, turbulence and pollutant emissions and thus is obviously an attractive solution for investigating the combustion characteristics at McDonald's Lime. There are a number of commercially available CFD codes, all of which contain sub models to account for the processes occurring during coal combustion. These include heating, devolatilization, and volatile and char combustion, together with the behaviour of spherical coal and ash particles.

The McDonald's Lime rotary kilns are currently fired by means of a single channel burner through which the transport air and pulverised coal travel. Single channel burners are long established technology (Nobis, 1991), developed well before CFD tools were available. Computational Fluid Dynamics will allow the burner to be investigated in greater depth than previous work has allowed with analysis of temperature profiles, velocity profiles and species concentrations as well revisiting previously discussed areas such as kiln aerodynamics.

The object of this study is to evaluate the accuracy of a commercial CFD code for modelling pulverised coal combustion using known experimental results from a small-scale furnace. A validated modelling setup is then used to characterize the combustion processes occurring within McDonald's Lime's Kiln Two. The work aims to help the company achieve a pulverised coal flame that produces the required heat transfer to the limestone bed with idealised recirculation (Mullinger, 1987), while being more environmentally and economically friendly. Future work will investigate firing waste oil as a substitute for pulverised coal and the effects this will have on aspects such as flame shape and heat transfer.

NUMERICAL MODELLING

Pulverised coal combustion was modelled using the commercial CFD code, FLUENT version 12. Turbulence was accounted for using the standard k-ε model, radiation using the discrete-ordinates model and the segregated pressure-velocity coupling scheme was used The chemistry occurring during coal combustion has been considered using a number of different approaches. During the validation case comparisons were made between the generalised finite rate model and the mixture fraction/PDF approach. Modelling of the McDonalds Lime kiln was undertaken using the mixture fraction/PDF approach due to the greater computational efficiency.

In addition to solving transport equations for continuity, momentum, energy, turbulence and combustion chemistry,

Fluent simulates the discrete second phase in a Lagrangian frame of reference. This second phase consists of spherical coal particles, dispersed in the continuous phase, that follow several heat and mass transfer relationships or "laws". Coal combustion modelling makes use of the Inert Heating, Devolatilization, Surface Combustion and Inert Cooling laws. The turbulent dispersion of particles is modelled using a stochastic tracking approach. All models are steady state and neglect the effects of gravity. A high burner momentum and preheated secondary air in both cases leads to a small Richardson number so buoyancy is assumed to have an insignificant effect on the flame dynamics.

Coal Devolatilization

The evolution of volatile gases is accounted for using the single rate devolatilization model. The single rate model (Badzioch & Hawksley, 1970) assumes that the rate of devolatilization is first-order dependent on the amount of volatiles remaining in the particle.

$$-\frac{dm_p}{dt} = k(m_p - (1 - f_{v,0} - f_{w,0})m_{p,0}) \qquad (1)$$

where m_p is the particle mass (kg), $f_{v,0}$ is the fraction of volatiles initially present in the particle, $f_{w,0}$ is the mass fraction of evaporating/boiling material (if wet combustion is modelled) and $m_{p,0}$ is the initial particle mass (kg). k is the kinetic rate (s^{-1}). This equation has the approximate analytical solution

$$m_p(t+\Delta t) = (1 - f_{v,0})(1 - f_{w,0})m_{p,0} + \left[m_p(t) - (1 - f_{v,0}) \times (1 - f_{w,0})m_{p,0}\right]e^{-k\Delta t} \qquad (2)$$

which is obtained by assuming that the particle temperature varies only slightly between discrete time integration steps. The kinetic rate, k, is defined by input of an Arrhenius type pre-exponential factor and an activation energy.

$$k = A_1 \exp(-E/RT) \qquad (3)$$

The activation energy was kept constant at E=7.4×10^7 J/kmol for all modelling while the pre-exponential factor A_1 was obtained from Badzioch & Hawksley (1970) based on the coal properties.

When injected into a turbulent diffusion flame coal particles are rapidly heated at rates higher than 10^4 K/s (Peters & Weber, 1996). Under such rapid heating conditions, substantially more volatiles are given off than under low heating rates (1 K/s). For this reason the ASTM proximate volatile matter content cannot be used for modelling devolatilization rates. Instead the so-called high temperature volatile yield must be used. For the case of modelling McDonald's Lime kiln the high temperature volatile yield has been estimated using the Chemical Percolation Devolatilization (CPD) model (Genetti & Fletcher, 1999; Pugmire, Solum, & Grant, 1992).

Char Combustion

Surface char combustion is accounted for using the Kinetic/Diffusion Reaction Rate model, which assumes that the surface reaction rate is determined either by kinetics or a diffusion rate. Fluent uses the model of Baum & Street (1971) and Field (1969) in which the diffusion rate,

$$R_1 = C_1 \frac{\left[(T_p + T_\infty)/2\right]^{0.75}}{D_p} \qquad (4)$$

and a kinetic rate,

$$R_2 = C_2 \exp(-E/RT_p) \qquad (5)$$

are weighted to yield a char combustion rate of

$$\frac{dm_p}{dt} = -\pi D_p^2 P_0 \frac{R_1 R_2}{R_1 + R_2} \qquad (6)$$

where P_O is the partial pressure of oxidant species in the gas surrounding the combusting particle and the kinetic rate R_2 incorporates the effects of chemical reaction on the internal surface of the char particle and pore diffusion. Fluent recasts Equation 6 in terms of the oxidant mass fraction, m_O, as

$$\frac{dm_p}{dt} = -\pi D_p^2 \frac{\rho R T m_O}{M_O} \frac{R_1 R_2}{R_1 + R_2} \qquad (7)$$

The particle size is assumed to remain constant in this model while the density is allowed to decrease.

Finite Rate Chemistry

The first approach used for solving the gaseous phase reactions is the generalized finite rate formulation. This method solves the species transport equations for reactant and product concentrations, in which the chemical reaction mechanism is explicitly defined. Fluent predicts the local mass fraction of species Y_i through the solution of a convection-diffusion equation for the ith species. This conservation equation takes the following general form:

$$\nabla \cdot (\rho \vec{v} Y_i) = \nabla \cdot \vec{J}_i + R_i + S_i \qquad (8)$$

where J_i is the diffusion flux of species i arising due to concentration gradients, R_i is the net rate of production of species i by chemical reaction, and S_i is the rate of creation by addition from the dispersed phase. An equation of this form is solved for N-1 species where N is the total number of fluid phase chemical species present in the system.

Turbulent mixing for most fuels controls the overall rate of burning. Fluent provides a turbulence-chemistry interaction model based on the work of Magnussen and Hjertager (1976), called the eddy-dissipation model. The net rate of production of species i due to reaction r, $R_{i,r}$, is given by the smaller of the two expressions below:

$$R_{i,r} = \nu'_{i,r} M_{w,i} A \rho \frac{\varepsilon}{k} \min_H \left(\frac{Y_H}{\nu'_{H,r} M_{w,H}} \right) \qquad (9)$$

$$R_{i,r} = \nu'_{i,r} M_{w,i} A B \rho \frac{\varepsilon}{k} \frac{\sum_P Y_P}{\sum_j^N \nu''_{j,r} M_{w,j}} \qquad (10)$$

where ν' is the stoichiometric coefficient for reactants, ν'' is the stoichiometric coefficient for products, and M is the molecular weight. Y_p is the mass fraction of any product species, P, and Y_H is the mass fraction of a particular reactant H. A and B are empirical constants equal to 4.0 and 0.5 respectively. This model relates the rate of

reaction to the rate of dissipation of the reactant and product containing eddies.

Mixture Fraction/PDF Chemistry

The second approach used for modelling gaseous phase combustion chemistry was the mixture fraction/PDF approach, which simplifies the combustion process into a mixing problem. This model involves the solution of transport equations for one or two conserved scalars (the mixture fractions). The thermochemical properties of the fluid are derived from the predicted mixture fraction distribution instead of solving individual species transport equations. Since the mixture fraction/PDF model does not require the solution of multiple species transport equations it is more computationally efficient than the species transport model. For the current work the coal volatiles and char were treated as a single fuel stream and the equilibrium chemistry model was used, which assumes that the chemistry is rapid enough for chemical equilibrium to exist at a molecular level. The mixture fraction can be written in terms of the atomic mass fraction as

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \tag{11}$$

where Z_i is the elemental mass fraction for element *i*. The subscripts *ox* and *fuel* denote the values at the oxidiser and fuel stream inlets respectively. The mixture fraction is a conserved scalar and its value at each control volume is calculated via the solution of the following transport equation for the Favre mean (density-averaged) value of *f*.

$$\nabla \cdot \left(\rho \vec{v} \bar{f}\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \bar{f}\right) + S_m \tag{12}$$

The source term, S_m, is due to the transfer of mass into the gas phase from reacting coal particles. In addition to solving for the Favre mean mixture fractions, Fluent solves a conservation equation for the mixture fraction variance, $\overline{f'^2}$.

$$\nabla \cdot \left(\rho \vec{v} \overline{f'^2}\right) = \nabla \cdot \left(\frac{\mu_t}{\sigma_t} \nabla \overline{f'^2}\right) + C_g \mu_t \left(\nabla \cdot \bar{f}\right)^2 - C_d \rho \frac{\varepsilon}{k} \overline{f'^2} \tag{13}$$

where $f' = f - \bar{f}$. The default values for the constants σ_t, C_g and C_d are 0.85, 2.86 and 2.0 respectively. Under the assumption of chemical equilibrium all thermochemical scalars (species fractions, temperature and density) are uniquely related to the instantaneous fuel mixture fraction.

$$\phi_i = \phi_i(f) \tag{14}$$

where ϕ_i represents the instantaneous species concentration, temperature or density. In a non-adiabatic system such as the two cases being studied the effect of heat loss/gain is parameterised as

$$\phi_i = \phi_i(f, H) \tag{15}$$

for a single mixture fraction system where *H* is the instantaneous enthalpy.

The effects of turbulence on combustion chemistry are accounted for using an assumed shape probability density function approach. The probability density function, *p(f)*, which describes the temporal fluctuations of the mixture fraction, *f*, in the turbulent flow is used to compute the averaged values of variables that depend on *f*.

Solution Procedure

A study was undertaken to find the modelling procedure that would lead to the fastest convergence. That procedure used throughout the current work is as follows.

1. Solve non-reacting flow for 300 iterations with no coupling between discrete and continuous phases.
2. Patch high temperature to burner region and solve one iteration to ignite flame.
3. Solve reactive flow performing 50 continuous phase iterations per discrete phase iteration (300 iterations).
4. Turn on Discrete Ordinates radiation model and solve for 500 iterations.
5. Change discretization scheme to second order for all equations with the exception of Discrete Ordinates. Solve for 300 iterations.
6. Turn on particle radiation interaction and solve until converged (typically around 3000-4000 iterations).

It is also worth noting the importance of using a very small under-relaxation factor (0.1) when modelling the combustion of small (1 μm) pulverised coal particles.

VALIDATION CASE

A validation study was undertaken to ascertain the accuracy of Fluent when modelling pulverised coal combustion. Experimental data was obtained for a 2.4 MW, swirl-stabilized, pulverised coal flame fired in the IFRF Furnace No. 1 (Peters & Weber, 1996). Measurements of in flame temperatures, velocities and chemical species concentrations are available for seven traverses of the furnace. Velocity measurements are available at four traverses.

Model Description

A three-dimensional quarter-geometry converged mesh containing 220,000 cells was constructed using Gambit. The mesh was refined in the burner region and areas of high velocity and temperature gradients. The coal fired in the IFRF Furnace was a Saar Coal: Gottelborn hvBb. The proximate and ultimate analyses of the coal are contained in Table 1, Table 2 contains additional coal properties used by Fluent and Table 3 contains the experimental burner input conditions. Other necessary boundary conditions such as wall temperatures and emissivities are listed in the work of Peters and Weber (1996).

Proximate Analysis (weight %, dry)	
Volatile Matter	37.4
Fixed Carbon	54.3
Ash	8.3
Ultimate Analysis (weight %, dry)	
Carbon	80.36
Hydrogen	5.08
Nitrogen	1.45
Sulphur	0.94
Oxygen (by diff.)	12.17

Table 1: Gottelborn coal proximate and ultimate analyses.

Coal Properties	
Coal particle density	1000 kg/m3
Coal particle specific heat	1100 J/Kg.K
Coal particle size distribution	Rosin-Rammler
Maximum size	300 µm
Minimum size	1 µm
Mean size	45 µm
Spread	1.36
LCV	32.32 MJ/kg (daf)
Coal thermal conductivity	0.0454 W/m.K
Volatile Matter Properties	
High temperature volatile yield	0.6 (daf)
Char Properties	
Oxygen diffusion rate	5×10^{-12} kg/m^2.s.Pa
Pre-exponential factor	6.7 kg/m^2.s.Pa$^{0.5}$
Activation energy	113.82 MJ/kgmole

Table 2: Additional Gottelborn coal properties.

At the combustion air inlet:	
Temperature	573.15 K
Mean axial velocity	43.83 m/s
Mean tangential velocity	49.42 m/s
Turbulent intensity	20%
At the pulverized coal and transport air inlet:	
Coal mass flow rate (dry)	0.0731 kg/s
Temperature	343.15 K
Mean axial velocity	23.02 m/s
Turbulent intensity	10%

Table 3: Burner inlet conditions.

Results and Discussion

The validation case aimed to compare results of the mixture fraction/PDF and finite rate modelling approaches to experimental measurements of the IFRF furnace. A Fluent tutorial modelling combustion in the same furnace using the finite rate combustion model (ANSYS, 2008) yielded the coal size distribution in the form of a detailed sieve analysis listing a mass flow for nine different particles sizes. A Rosin-Rammler distribution was calculated for this sieve analysis and found to be almost identical to that provided by Peters and Weber (1996). Modelling of the IFRF furnace was undertaken using firstly a single injection with a Rosin-Rammler distribution and secondly with nine separate injections, each having a uniform particle size and the appropriate mass flow rate. The results in Figure 1 demonstrate how the Rosin-Rammler distribution returns a hotter, and less accurate temperature than the multiple injection case. This suggests that the Rosin-Rammler distribution is not providing an accurate representation of the coal particle size distribution in the IFRF furnace and that where possible it would be advisable to directly use a sieve analysis to define the size of pulverised coal injections. These results highlight the overall effect size distribution can have on temperature profiles and how important it is to obtain accurate particle size information when undertaking combustion modelling with CFD.

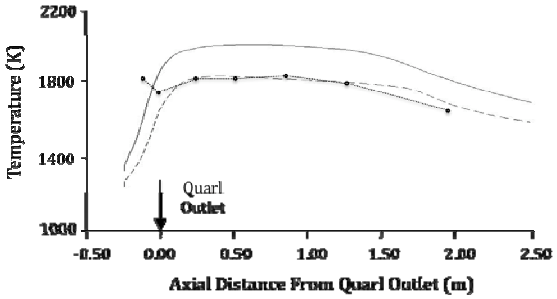


Figure 1: Centre line temperature profile of the IFRF furnace for; experimental results (o), single injection with a Rosin-Rammler size distribution (——), and multiple injections with a uniform size distribution (– – –).

Figure 2 shows a comparison of the centre-line temperature profiles for the mixture fraction/PDF and finite rate chemistry models. Both cases use multiple uniform sized injections of pulverised coal particles. Neither model correlates well with the experimental results inside the high swirl quarl zone, however the finite rate model provides a good correlation outside of this area. The mixture fraction/PDF model is however approximately 200K hotter.

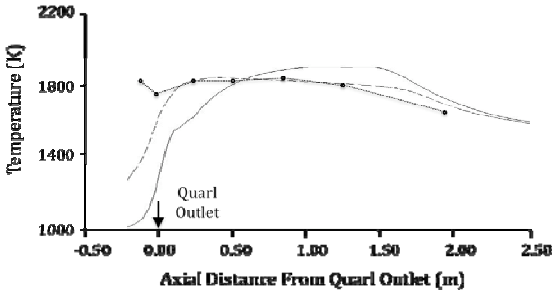


Figure 2: Centre line temperature profile of the IFRF furnace for; experimental results (o), mixture fraction/PDF approach (——), and finite rate approach (– – –).

While the finite rate approach to combustion chemistry correlates very well with experimental data, there are issues with convergence and computational time when using this approach in the much larger McDonald's Lime kiln model. This is likely caused by the greater number of transport equations that must be solved in comparison to the mixture fraction/PDF approach. As a result, further modelling of the McDonald's kiln will be undertaken using the mixture fraction/PDF approach. While less accurate, it is felt this approach will provide useful insight into the general combustion characteristics of the kiln.

As previously mentioned, neither of the combustion chemistry models were very accurate in the high swirl region close to the burner, however further downstream both chemistry models and the experimental results correlated well. This suggests that there may be issues with the way the model handles highly swirling flow. Future work may investigate this theory further in the hope of improving the overall model accuracy.

LIME KILN MODELLING

McDonald's Lime Ltd in Otorohanga, New Zealand wish to investigate the performance of the current pulverised coal firing system used in their larger 300t/day kiln.

Model Description

Kiln 2 is fired with pulverised Environ coal through a single tube burner pipe. Preheated combustion air enters through the firing hood from the product cooler. Air exits at the rear end into a preheater and is also extracted off the firing hood for use in the coal mill. A simple schematic of the modelled portion of the McDonald's Lime kiln is shown in Figure 3.

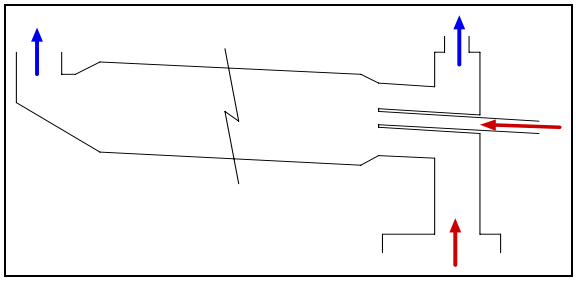


Figure 3: Schematic showing inlets (red) and outlets (blue) of the McDonald's Lime kiln model.

The geometry of the kiln was created using Solidworks before being imported into the mesh generation software Harpoon where a two million cell hex-dominant mesh was created. The mesh was then refined in areas of high temperature and velocity gradients to give a grid independent 3.6 million cell mesh. Any effects of the rotating wall have been ignored in this work, as with a rotational speed of approximately 1 RPM the axial velocities are orders of magnitude greater than tangential velocities. Therefore rotation is unlikely to have any significant effects on the flame dynamics

Table 4 contains the proximate and ultimate analyses of the Environ coal fired by McDonald's Lime, while Table 5 contains additional properties that are required for modelling coal combustion in Fluent. The initial modelling work detailed in this paper ignored any effects of moisture and used the properties of dry coal. The 5.2% moisture present in the as-fired Environ coal was calculated to have little effect on the total kiln heat output and literature also points towards coal moisture content having little effect on furnace temperature profiles (Bosoaga et al., 2006). While multiple uniform sized injections provided better accuracy in the validation case, a Rosin-Rammler size distribution was used because of the poor quality of the supplied sieve analyses. Over 55% of the mass passed through the smallest sieve. This is an area that is currently being improved.

Proximate Analysis (weight %)		
	As fired	Dry
Volatile Matter	39.5	41.7
Fixed Carbon	46.7	19.2
Ash	8.6	9.1
Moisture	5.2	
Ultimate Analysis (weight %, dry)		
Carbon		74.91
Hydrogen		5.18
Nitrogen		1.27
Sulphur		0.32
Oxygen (by diff.)		18.31

Table 4: Environ coal proximate and ultimate analyses.

Coal Properties	
Coal particle density	1400 kg/m^3
Coal particle specific heat	1200 J/Kg.K
Coal particle size distribution	Rosin-Rammler
Maximum size	300 µm
Minimum size	1 µm
Mean size	45 µm
Spread	1.56
LCV	20.42 MJ/kg (daf)
Coal thermal conductivity	0.0454 W/m.K
Volatile Matter Properties	
High temperature volatile yield	60% (dry)

Table 5: Additional Environ coal properties.

Further coal particle information unavailable from the supplied analyses was estimated from literature. Table 6 contains the air and coal flow parameters that are a combination of on-site measurements and assumptions. It is assumed that all air enters through the four defined inlets and outlets and that there are no other air leaks in or out of the kiln.

At the combustion air inlet:	
Temperature	1013K
Mean axial velocity	2.96 m/s
Inlet Area	8.76 m^2
Turbulent intensity	10%
At the pulverized coal and transport air inlet:	
Coal mass flow rate (dry)	0.8594 kg/s
Temperature	337.7 K
Mean axial velocity	33.14 m/s
Inlet Area	0.087 m^2
Turbulent intensity	10%
Outlet Locations:	
Firing hood hot air duct	-12.5 Pa
Preheater outlet	-300 Pa

Table 6: Burner inlet conditions.

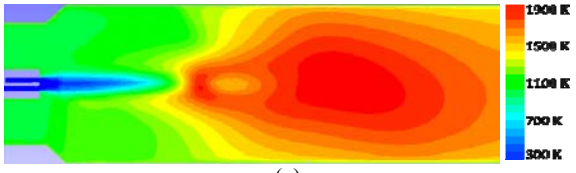
Initial modelling work has neglected the effects of the limestone bed as it endothermically decomposes to CaO. This causes a mass transfer of CO_2 into the continuous phase and energy transfer into the bed. The focus of this work is on characterising pulverised coal combustion in the McDonald's kiln that can in future be compared to a hybrid coal and waste oil firing system. As a result the walls have been set at a constant temperature, which greatly simplifies the problem from the complex setup needed when effects of the bed are taken into account. Because the bed fills approximately 15% of the cross-sectional kiln area, neglecting it is unlikely to effect the flame dynamics, however neglecting the bed heat and mass transfer is likely to affect the overall temperature and species distributions in the kiln. Therefore, it becomes hard to take quantitative numbers from CFD modelling results, the work instead moves towards making relative comparisons between two different combustion setups.

Results and Discussion

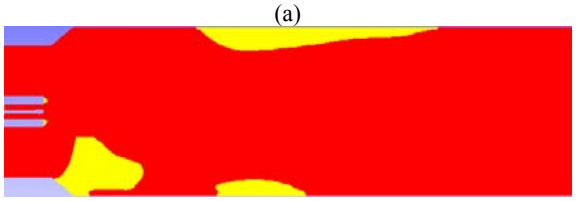
The computational models were solved using the Univeristy of Canterbury's IBM p575 High Powered Computer using 16 processors. Each simulation took approximately 30 hours to solve.

Investigations into the rotary kiln combustion characteristics are still in the early stages however initial work focussed on two aspects, recirculation of combustion air, and the effects of the coal flow rate on temperature profiles. Recirculation of combustion air is important as it can inhibits the flame from impinging on the kiln wall and bed, thus preventing undesired levels of heat transfer to these areas.

Figure 4 shows contour plots for velocity and temperature in the flame region of the rotary kiln. Figure 4(a) is a plot of the z-direction velocity with red indicating a positive velocity and yellow a negative velocity (recirculating flow). The longer portion of recirculation in the upper region of the kiln appears to be driving the hottest temperature region downwards. These results indicate that there may be excessive heat transfer being passed to the limestone bed in the kiln and therefore future work will discuss these recirculation characteristics and whether improvements can be made to the kiln aerodynamics.



(a)



(b)

Figure 4: (a) Temperature profile in the flame region of the McDonalds Lime kiln (b) Contours of positive (red) and negative (yellow) z-direction velocity.

Figure 5 shows the centre line temperature profile of the McDonalds Lime kiln for two different coal flow rates (difference of 13%). Moving downstream from the burner the temperature increases sharply before both cases show a dip in temperature, more so for the higher flow rate. Futher downstream the greater coal flow produces a slightly higher temperature, however towards the rear end of the kiln there is little difference between the two cases.

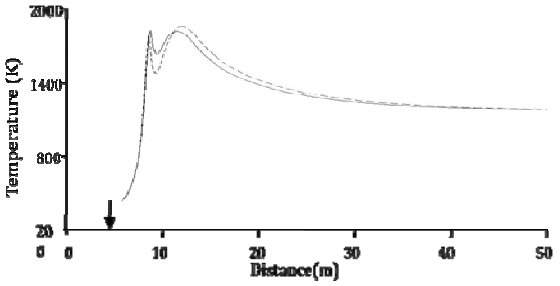


Figure 5: Centre line temperature profile of the McDonalds Lime kiln for a coal flow rate of 0.7594 kg/s (−−−) and 0.8594 kg/s (− − −).

CONCLUSION

Computational Fluid Dynamics has been used as a tool for modelling pulverised coal combustion. CFD was first validated using experimental results from the IFRF Furnace No. 1. The validation experiments showed the finite rate model to produce a better representation of combustion characteristics than the mixture fraction/PDF approach to combustion chemistry. The validation case also demonstrated that multiple uniform sized injections provide more accurate results than a single injection with a Rosin-Rammler particle size distribution.

The mixture fraction/PDF model was used to model combustion in a large-scale rotary lime kiln due to its computational efficiency. The combustion modelling showed how recirculation in the rotary kiln is affecting the temperature profile. The effects of coal flow rate on temperature were also investigated with a 13% difference in mass flow found to have little affect on the centre line temperature profile. The combustion modelling undertaken thus far is still in the early stages however it has provided some promising results and laid the foundation for future modelling of both coal combustion and a hybrid fuel system of coal and waste oil.

REFERENCES

ANSYS, I. (2008). Tutorial: Coal combustion with Eddy Break Up (EBU) Model.

BADZIOCH, S., and HAWKSLEY, P. G. W. (1970). Kinetics of Thermal Decomposition of Pulverized Coal Particles. *Ind. Eng. Chem. Process Des. Develop. , 9*(4), 521-530.

BAUM, M. M., and STREET, P. J. (1971). Predicting the Combustion Behaviour of Coal Particles. *Combustion Science and Technology, 3*(5), 231-243.

BOSOAGA, A., PANOIU, N., MIHAESCU, L., BACKREEDY, R. I., MA, L., POURKASHANIAN, M., et al. (2006). The combustion of pulverised low grade lignite. *Fuel, 85*, 1591-1598.

FIELD, M. A. (1969). Rate of Combustion of Size-Graded Fractions of Char from a Low Rank Coal between 1200K - 2000K. *Combustion and Flame, 13*, 237-252.

GENETTI, D., and FLETCHER, T. H. (1999). Development and Application of a Correlation of C NMR Chemical Structural Analyses of Coal Based on Elemtntal Composition and Volatile Matter Content. *Energy & Fuels, 13*, 60-68.

MAGNUSSEN, B. F., and HJERTAGER, B. H. (1976). On mathematical models of turbulent combustion with the special emphasis on soot formation and combustion. In *International Symposium on Combustion*. Vol. 16, (The Combustion Institute).

MULLINGER, P. J. (1987). Rotary kiln coal firing part II: Burner design. *ZKG International, 40*(5), 259-294.

NOBIS, R. H. (1991). Latest Rotary Kiln Burner Technology: Possibilities and Experiences. *IEEE Transactions on Industry Applications, 27*(5), 798-806.

PETERS, A. A. F., and WEBER, R. (1996). Mathematical Modelling of a 2.4MW Swirling Pulverized Coal Flame. *Combustion Science and Technology, 122*, 131-182.

PUGMIRE, R. J., SOLUM, M. S., and GRANT, D. M. (1992). Chemical Percolation Model for Devoaltilization. 3. Direct Use of C NMR Data To Predict Effects of Coal Type. *Energy & Fuels, 6*, 414-431.