OPTIMISATION OF FURNACE DESIGN FOR IN-FURNACE NO_X REDUCTION

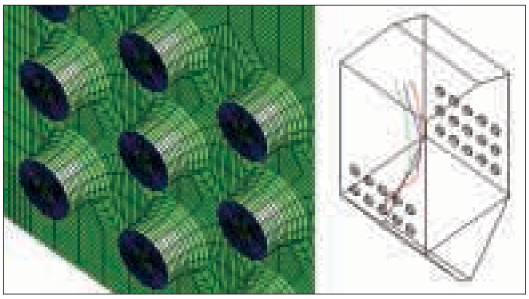

Figure 1. caption

OBJECTIVES

- To determine the optimum burner size relative to furnace dimensions
- To determine the minimum acceptable pitch between adjacent burners and between the wing burners and furnace side walls
- To investigate the effect of interleaving the burner pitches in opposed wall fired plant in order to increase furnace utilisation and improve the turndown characteristics of the plant
- To investigate whether biasing of fuel or air across a burner row offers significant improvements in NO_x levels without adversely affecting carbon burnout

SUMMARY

Retrofit installations of low NO_x systems are often constrained to some extent by the configuration of the existing plant. These practical constraints can be avoided in the design process for new plant. Factors such as the size, number and pitching of burners are selected to optimise furnace performance in terms of heat input, residence time, corrosion, pollutant formation and economics. The identification of optimum burner size and pitch with particular regard to NO_x emissions and carbon burnout is of significant interest.

The complex process of coal combustion can be simulated with some degree of accuracy by means of Computational Fluid Dynamics (CFD) modelling. This represents a valuable technique for the analysis of the effect of various factors on combustion performance and pollutant (NO_x) formation.

A review of existing front and opposed wall furnace designs found that for furnace sizes of 300 and 500 MWe, the typical thermal ratings of the burners employed are between 40 and 60 MWth. A non-dimensionalised horizontal, vertical and wall clearance pitch value of around 2.75d (2.75 x throat diameter) was representative of the units examined, with a number of units featuring burners having considerably tighter pitches (around 2d). The review also allowed the specification of the dimensions of generic furnaces for modelling purposes.

Physical modelling of utility furnaces can be undertaken to obtain accurate flow measurement data. Data was obtained from a 1/10th scale perspex model of a generic front wall fired furnace. The measured data was used to validate the use of CFD techniques to investigate the effect of changes to furnace configuration.

The effect of the variation of the number and size of burners was investigated in a front and an opposed wall fired furnace. Results established that fewer large burners are preferable to a larger number of smaller burners in terms of lower NO_x (fuel and thermal) and plant economics, without adversely affecting carbon in ash (CIA). The predictions were consistent with previous studies of the effect of scaling criteria. Air biasing or 'off-stoichiometric' firing was also investigated. NO_x reductions predicted were poor, in line with plant experience.

As pitch was reduced in a generic opposed wall fired furnace, flames became narrower, with a merging of tertiary air streams, a lessening in strength of the internal recirculation zone and a flaring out of flow to occupy available volume. Although fuel NO_x showed little variation with reducing pitch, thermal NO_x and CIA increased. The minimum acceptable pitch was identified. An additional study showed the sensitivity of fuel NO_x to excess air level, and predictions from the CFD model were consistent with plant experience.

The novel technique of burner interleaving in opposed wall fired furnaces was evaluated. Significant NO_x reductions were gained through vertical interleaving but at the expense of higher CIA. The analysis of the design of the OFA systems applied to the front and opposed wall fired furnaces gave reductions in NO_x comparable with expectations. Little or no NO_x reduction benefit can be expected to accrue from the use of interleaving on opposed wall fired furnaces with deeply staged OFA systems, as staging becomes the limiting factor for NO_x generation.

COST

The total cost of the project was £253 560, with the Department of Trade and Industry contributing £126 780 (50%). The balance of the project funding was provided by the participants.

DURATION

24 months – January 2000 to December 2001

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CLEANER COAL TECHNOLOGY PROGRAMME

Project Summary 329

BACKGROUND

Potential limitations to low NO_x system retrofit installations include the furnace dimensions or accessibility to the furnace for fitting of reburn fuel or overfire air (OFA) ports. For new plant, however, such practical constraints can largely be avoided in the design process where allowances can be made for the installation of NO_x control equipment.

Primary NO_x control is achieved by low NO_x burners but it is considered that the optimisation of burner size and pitching arrangement can lead to improved utilisation of the furnace volume, lower NO_x levels and a reduced sensitivity to burner/burner interactions. Of particular interest is the effect of varying burner thermal rating on NO_x and carbon burnout.

Burner manufacturers and utility plant operators alike share the concern that the interaction of burner flames within multi-burner furnaces may represent a significant contribution to NO_x levels. Therefore there exists a requirement for an increased understanding of burner interaction effects within multi-burner furnaces.

Interleaving involves the offset of opposing burners within opposed wall fired plant, and may serve as a viable NO_x reduction technique in new plant. However, novel concepts such as this must be proven to be of technical and economic value.

Furnace air staging is often used in conjunction with low NO_x burners. Typically the arrangement of OFA ports is optimised with respect to the particular furnace of interest. The impact of wall firing type and changes to burner arrangement on global furnace mixing and thus OFA effectiveness represents an important consideration.

In order to investigate these issues it is necessary to adopt a mathematical modelling approach, as the parameters of interest are not readily adjustable in practical situations.

Combustion modelling was undertaken using Computational Fluid Dynamics (CFD) to predict temperature, flow and species profiles, as well as NO_x and carbon in ash (CIA), within the various furnace arrangements. Validation of the flow field prediction was achieved by comparison against detailed measurements carried out in a physical model.

FURNACE REVIEW

Past research found that burner crowding leads to reduced large scale mixing and entrainment of air and flue gas from the surroundings, causing higher flame temperatures and longer flames. Worst case interactions occur where there are tightly pitched low swirl burners. The principal furnace dimensions of interest with regard to flame interactions are width, depth, burner horizontal and vertical pitch, and burner side wall clearance.

Front and opposed wall fired furnace designs were reviewed. For furnace sizes of ~300 and ~500 MWe, the typical thermal rating of the burners employed is between ~40 and ~60 MWth. A non-dimensionalised horizontal, vertical and wall clearance pitch value of around 2.75d (2.75 x burner throat diameter) was found to be representative of the units examined. However there are a number of units with considerably tighter pitches and it will be here that the problems associated with flame interactions may become significant.

The findings of the review were used to define typical and variant furnace arrangements for the purposes of the physical and mathematical modelling activities

PHYSICAL MODELLING AND CFD VALIDATION

A 1/10th geometric scale physical model of a front wall fired furnace was constructed. The model burners feature unswirled primary and swirled secondary air registers as well as a core air tube (blocked to give zero flow). The model has the flexibility to allow the wing burner to furnace wall clearance to be maintained with changing burner pitch. Burner array panels set on square pitches of 1.6d, 1.75d, 2d and 2.25d were manufactured, and the interchangability of the burners allowed swirl pattern (columnar or checkerboard) to be investigated.

Figure 2. Physical Model of Multi-Burner Furnace

It was shown that the CFD model was able to reproduce the physical model flow field with a reasonable degree of accuracy. In particular it was possible to simulate the changing strength of the internal recirculation zone and interactions between adjacent burners in an isothermal physical model of a multiburner furnace. The modelling of multiburner utility plant can therefore be undertaken with confidence in the prediction of the underlying flow field.

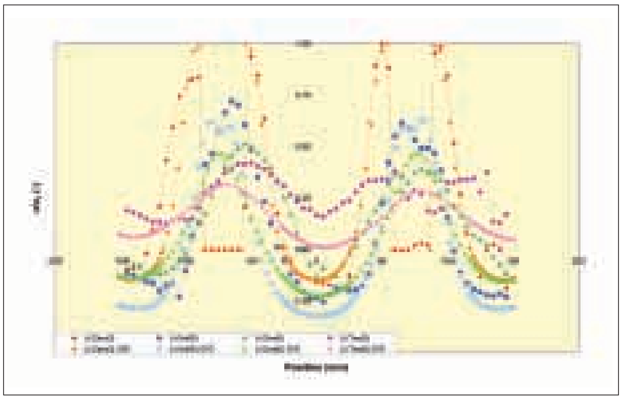

Figure 3. Physical Model vs CFD – Velocity Profiles

MODEL DEFINITION

All models were constructed using hexahedral cells for the accurate resolution of complex swirling flows and, where possible, advantage was taken of centreline symmetry conditions. The arch level was chosen as the furnace exit for all models. Fuel and air flows and temperatures were specified based on low NO_x burner operation, firing a typical UK bituminous coal. The proportions of volatiles, fixed carbon and inert ash are based on the standard proximate analysis of the coal used. However, a modification was made to account for the additional yield of volatiles due to the high heating rates and temperatures that are experienced by the coal in full scale plant. This was defined by measurements made on a High Temperature Wire Mesh.

Particle tracking serves as a useful tool in CFD modelling. Along a particle's trajectory the principal factors that contribute to its burnout profile are time, temperature and O_2 concentration. Sample particle tracking was carried out for all CFD combustion cases to aid analysis.

BURNER VERSUS FURNACE SIZE

The effect of burner size was investigated on a 500 MWe front wall fired furnace and 550 MWe opposed wall fired furnace. Each furnace was modelled with low NO_x burners of notionally 37 and 70 MWth rating. The thermal capacity and number of burners was altered whilst maintaining the overall furnace envelope and extent of the burner zone. Therefore the thermal environment within the furnace as a whole is the same for both burner sizes.

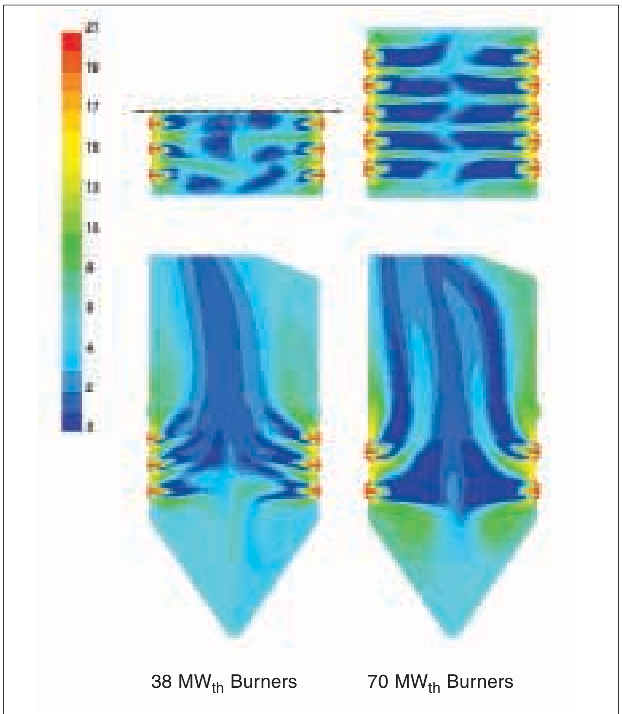

Figure 4. Opposed Wall Fired Furnace – Contours of O_2 Conc'n (%)

Predicted fuel NO_x figures showed a good degree of consistency between firing type, with reductions (15-20%) in fuel NO_x arising from an increase in thermal rating from 37 to 70 MWth. A decrease in thermal NO_x emission (20-30%) front, also accompanied an increase in burner thermal rating. Unburned losses were low for all cases.

The findings were found to be consistent with previous research by IFRF, which investigated the effect of reducing burner scale when using different scaling criterion. When considering constant-velocity scaling, flame chemistry becomes dominant over mixing as scale is reduced and so a higher NO_x emission results from rapid fuel and air mixing.

AIR BIASING

The biasing of air across and between burner rows was investigated on a 550 MWe opposed wall fired furnace. No significant reduction in fuel NO_x arose from either biasing arrangement modelled, due to the high excess air levels applied to the fuel lean burners. An unacceptably high unburned loss originated from the fuel rich furnace centre associated with horizontal biasing. Vertical biasing, which achieved good burnout and lower thermal NO_x emission than baseline, may merit future consideration.

Plant experience of 'off-stoichiometric' firing gives rise to NO_x reductions of typically 10 to 15%. The CFD predictions gave comparable results.

BURNER PITCHING

A generic opposed wall fired furnace was used to study the effect of burner pitching on flame interactions. Furnace side wall and bottom row burner-to-hopper clearances were held constant between models and therefore furnace width increases with burner horizontal pitch. Hopper and total furnace height were maintained between cases, with the arch level representing the exit from the model. Each quarter-furnace model features 9 advanced low NO_x burners set on a square pitch and arranged in a 3 rows high by 3 columns wide array. The chosen pitching levels were 1.3d, 1.5d, 1.75d, 2d, 2.25d, 2.5d and 2.75d.

Flame shape was altered considerably with flames becoming narrower as pitch was reduced. A number of trends, consistent with the increased confinement of the burner flows, were evident in the form of a merging of tertiary air streams, a lessening in strength of internal recirculation zone and flaring out of flow to occupy available volume.

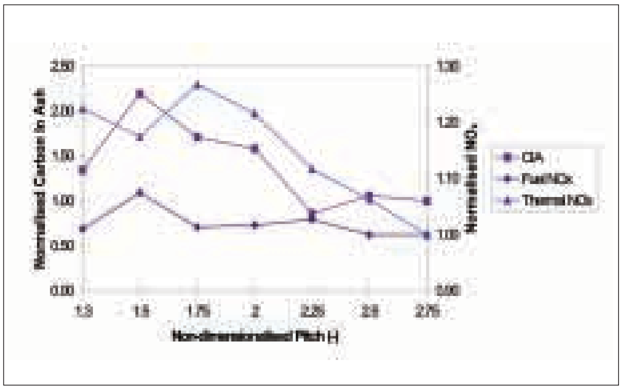

Figure 5. Effect of Pitch on NO_x and Carbon In Ash

Tighter pitches showed peak temperatures being reached further down-stream and a lower availability of oxidant. However, with the tightest pitch modelled, flame tails mixed more readily with tertiary air and this promoted better burnout.

Reducing burner pitch through the range 2.75d to 1.3d had little effect on fuel NO_x emission. With the tighter pitches, lower initial temperatures in a highly oxidising environment, were followed by high temperatures in an oxidant lean environment, conditions favourable to fuel NO_x reduction. Thermal NO_x increased steadily with reducing pitch until breakdown of the flame structure. Unburned loss increased gradually as pitch varied through 2.75d to 1.5d. The unburned loss at 1.3d was found to be lower, consistent with the observation stated above.

The effect of pitch, excess air and quarl angle on NO_x and carbon burnout was investigated by means of a Taguchi Analysis. The use of orthogonal (fractional factorial) arrays is the main basis of the Taguchi method. Time and cost savings are achieved when using this approach. An "L4" array, comprising four experiments, as opposed to eight in the corresponding full factorial test matrix, was utilised to investigate the effect of three factors at two levels. This activity served as a means of trend validation for the burner pitching investigation in addition to giving an insight into the effect of the additional variables.

The influence of pitch on fuel NO_x and carbon burnout was found to be minimal, consistent with the findings of the pitching study. Excess air had a significant impact, an increase bringing about higher fuel NO_x and lower carbon burnout. Trends observed in experimental studies were reasonably reproduced by CFD. The impact of burner quarl angle was slight.

BURNER INTERLEAVING

A 550 MWe opposed wall fired furnace featuring 70 MWth low NO_x burners was used to investigate the effect of burner interleaving. Two scenarios were considered:

- Horizontal interleaving, front and rear wall burners staggered by a quarter pitch
- Vertical interleaving, with front wall burners elevated by half a pitch

Horizontal interleaving gave rise to fuel and thermal NO_x reductions of 8 and 28%, respectively, accompanied by an increase in unburned loss. Total NO_x reduction was 18%. NO_x production was restricted through lower burner zone temperatures and exhaustion of oxidant, with longer flames testifying to this.

Vertical interleaving reduced fuel NO_x by 20%, and thermal NO_x by 61%. The reduction in total NO_x was 35%. This was attributed to a significant change in burner zone thermal environment – temperatures being considerably lower. A further increase in unburned loss was predicted.

BURNER ARRANGEMENT AND OFA INJECTION

A standard primary zone stoichiometry and residence time between the top row of burners and OFA ports was applied to all models. The number of OFA ports, velocities and swirl levels were defined based on the findings of the DTI project: 'Optimisation of Furnace Mixing to Enhance Combustion Efficiency in Advanced Low NO_x Systems'. The following models were set-up:

- 500 MWe front wall fired with 70 MWth burners
- 550 MWe opposed wall fired with 70 MWth burners
- 550 MWe opposed wall fired with 70 MWth burners, and vertical interleaving

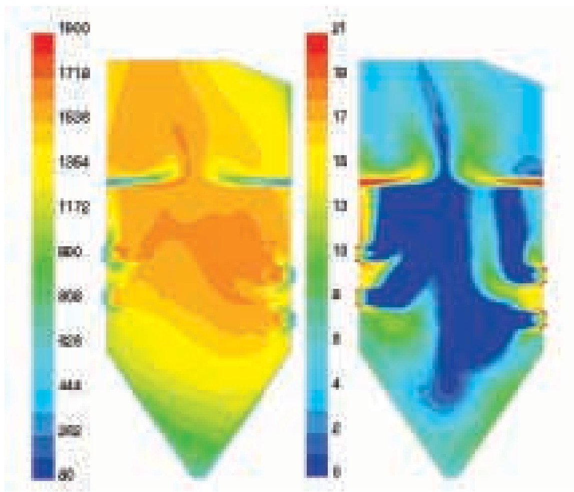

Figure 6. Staged Opposed Wall Fired Furnace, Vertical Interleaving – Contours of Temperature and Oxygen Concentration

For the front wall fired furnace, the use of OFA reduced fuel NO_x by 41% and thermal NO_x by 25%. A reduction in total NO_x of 41% was predicted. Lower fuel NO_x reductions were achieved with opposed wall fired furnace staging (32%). Thermal NO_x reductions were considerably higher (71%), with a total NO_x reduction of 49%.

The application of OFA to an opposed wall fired furnace with vertically interleaved burners achieved slight NO_x reductions (23% fuel and 13% thermal, 23% total) relative to single stage case. Comparing the non-interleaved OFA furnace with interleaved OFA, fuel NO_x was slightly lower, and thermal NO_x slightly higher, for the interleaved case.

Little or no NO_x reduction benefit can be expected to accrue from the use of interleaving on opposed wall fired furnaces with deeply staged OFA systems, as staging becomes the limiting factor for NO_x generation.

The design of the OFA systems applied to the front and opposed wall fired furnaces was deemed to be effective. However, refinements could be made to number of ports, locations and operating conditions to further improve mixing.

Combustion CFD modelling can be used to predict the relative effectiveness of OFA systems, with predicted NO_x reductions being comparable to plant experience.

CONCLUSIONS

The following conclusions were reached from the work undertaken:

- The typical burner size employed in existing front and opposed wall fired furnaces, of 300 and 500 MWe, is between 40 and 60 MWth.
- A non-dimensionalised horizontal, vertical and wall clearance pitch of 2.75d was deemed to be representative of all units studied. However, several units feature tighter pitches.
- Comparison of physical model data with predictions from a CFD model of the physical model showed reasonable agreement. Mathematical modelling, for the prediction of the flow field within a multi-burner furnace, can therefore be applied with confidence.
- For lower NO_x emission, with no carbon burnout penalty, fewer larger burners are preferable to more burners of a lower thermal heat input. Employing larger burners is also economically advantageous.
- Modelling predictions were found to be consistent with previous research by IFRF into the effect of burner scaling technique on NO_x emission. When considering constant-velocity scaling, flame chemistry becomes dominant over mixing as scale is reduced and so a higher NO_x emission results from rapid fuel and air mixing.
- Air biasing between burners gave rise to little or no NO_x reduction benefit, in line with plant experience. Vertical biasing of air between burner rows may merit further study in particular situations.
- Reducing burner pitch changed the flame shape considerably, with tertiary air streams merging and internal recirculation zone strength lessening with reducing pitch.
- Fuel NO_x showed little variation with tightening pitch, whereas thermal NO_x and unburned loss increased steadily. The minimum acceptable pitch was identified.
- Reductions in NO_x can be achieved with both horizontal and vertical interleaving arrangements. Vertical interleaving gave the highest reduction in NO_x, with a burnout penalty.
- A staged opposed wall fired furnace gave a greater NO_x reduction than a similarly staged front wall fired furnace. A vertically interleaved, staged opposed wall fired furnace gave only a slight additional reduction in NO_x.
- Combustion CFD modelling of air staging has been shown to predict NO_x reductions that are comparable with plant experience.

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