DESIGN AND OPERATION OF COAL-FIRED TURBO® FURNACES FOR NO_X CONTROL

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ABSTRACT

A parametric analysis performed on NO_X text data from four (4) coal fired dry bottom Turbo Furnaces is discussed. Total NO_X emissions are found to be strongly dependent on stoichiometry and secondary air mixing patterns. Conversely, NO_X emissions, for this data sample, appear to be only weakly dependent on the fuel nitrogen content. Several different coal types are included in the evaluation. NO_X correlation functions are also presented for selected burner secondary air vane positions. An optimum vane setting is identified which alters the air/fuel mixing pattern and reduces NO_X emissions.

INTRODUCTION

The focus of current research concerned with NO_X emissions from pulverized coal flames is centered on the development of control technologies to reduce or minimize the oxidation of chemically bound nitrogen in the coal. Both laboratory measurements[1,2] and utility boiler test data[3] indicate that the fate of fuel nitrogen is significantly affected by aerodynamic mixing patterns in the flame and combustion process variables such as excess air. The mixing schedule early in the combustion process appears to be of critical importance in nitrogen conversion.

Field data from various coal fired Riley dry bottom Turbo Furnaces are presented here along with a parametric evaluation of the results. The major variables affecting NO_X emissions in the Turbo Furnace design are determined and discussed. Insights into the combustion process from independent studies and from aerodynamic mixing studies in an isothermal Turbo Furnace model are used in the evaluation.

The field tests were performed under Riley's ongoing NO_X control research program. Measurements were obtained at various load and burner operating conditions from four (4) different steam generating dry bottom Turbo units ranging in size from 250,000 to 2,000,000 lb/hr. The data also include results from coals of differing nitrogen content and rank.

FURNACE DESIGN FEATURES

The dry bottom Turbo Furnace design, as shown in Figure 1, is characterized by a venturi shaped bottom with burners on opposite walls tilted downward. This furnace geometry provides an effective aerodynamic system for utilization of the lower furnace cooling surface. Non-swirl burners are used to delay the mixing of secondary air into the fuel jet, thereby, producing a low temperature diffusion controlled flame. Directional vanes are incorporated in the burner design to provide control over the schedule of this secondary air mixing. A description of these directional flame burners is given by the diagram in Figure 2. Fuel and air are introduced to the combustion chamber through slots formed in the downward facing waterwalls.

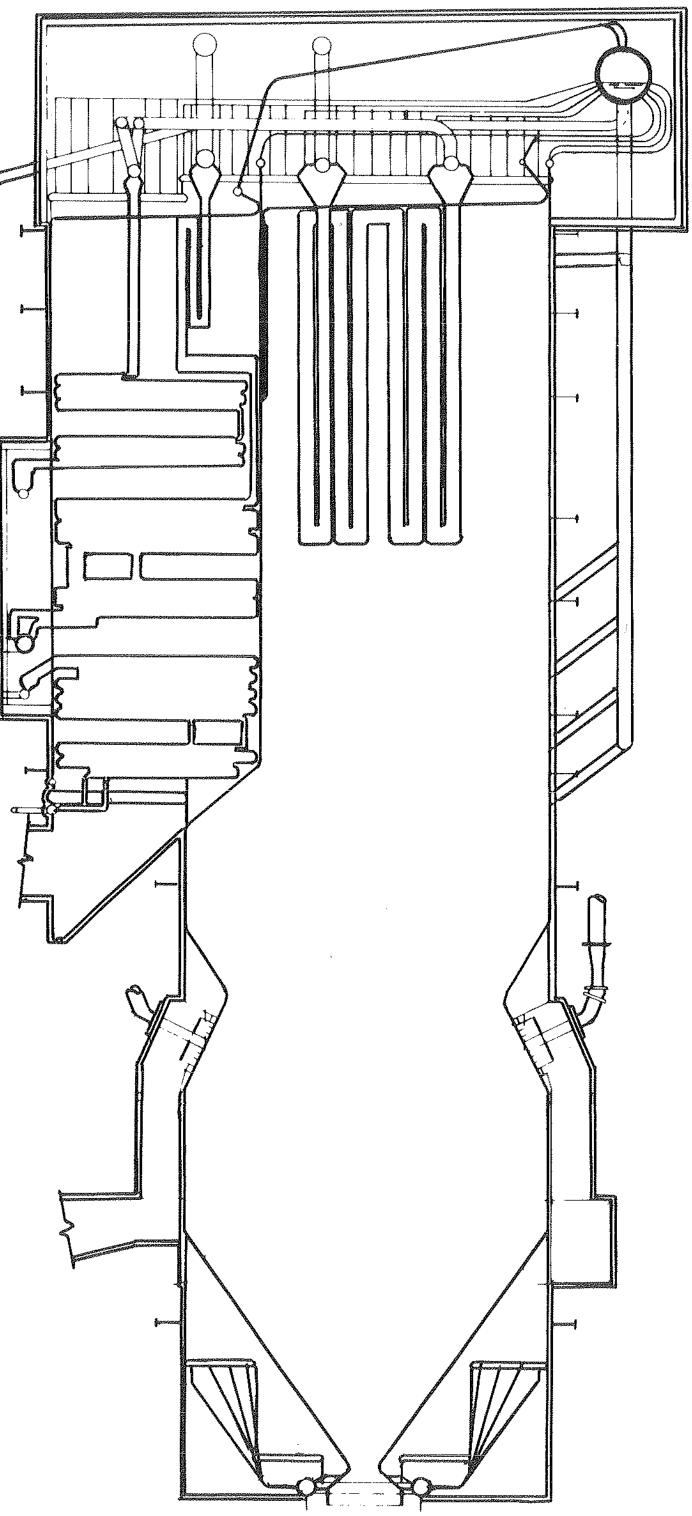

Figure 1 Riley Dry Bottom Turbo Furnace

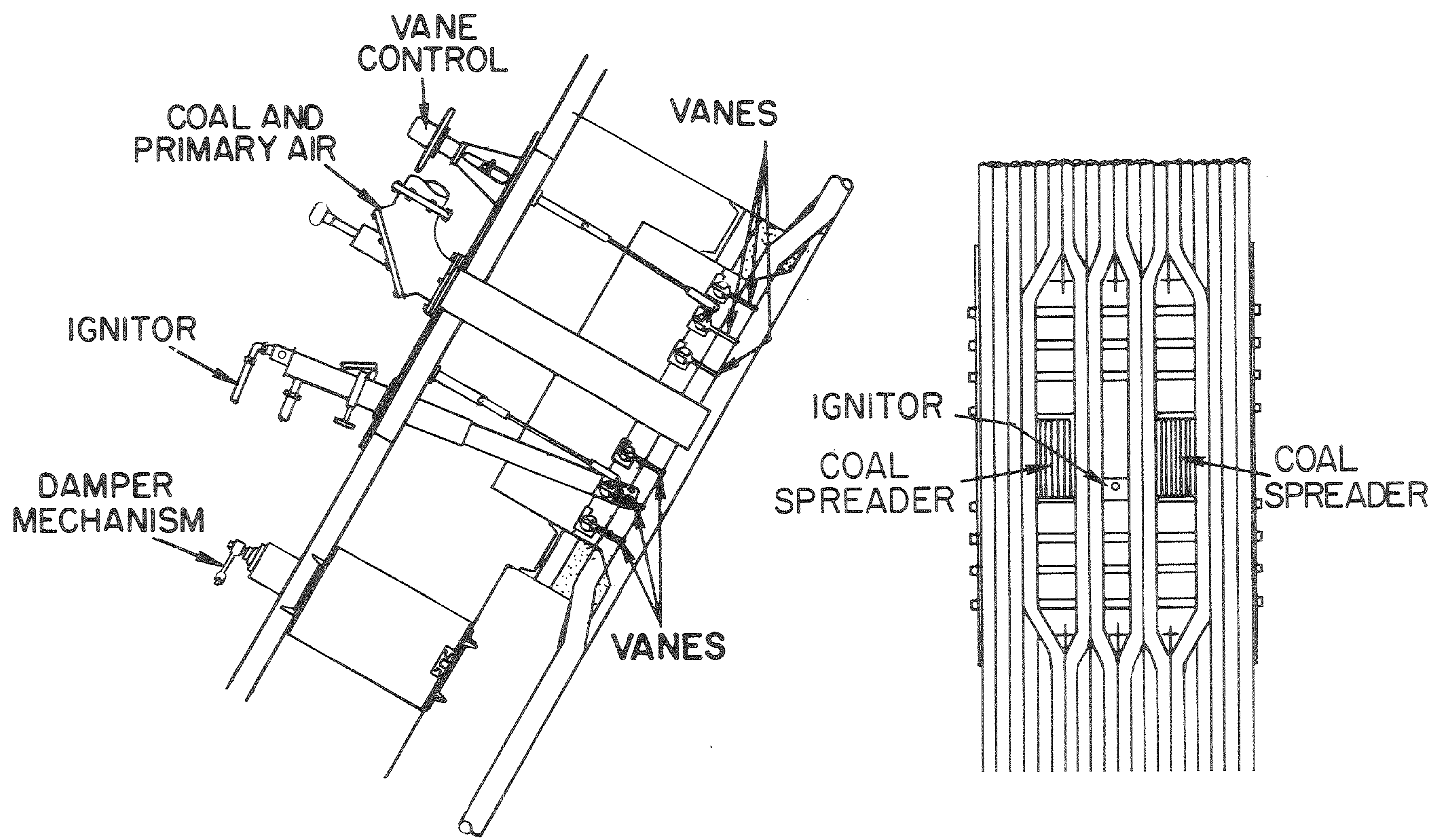

Figure 2 Riley Directional Flame Burner

AERODYNAMIC MIXING

Furnace flow patterns in such a combustion configuration are complex. To obtain information on flow and mixing conditions in the Turbo Furnace design, therefore, isothermal flow studies using cold air were conducted in a three dimensional 1/16th scale model of a utility sized prototype. Mixing patterns in the lower furnace are related to both the structural dimensions of the furnace chamber and burner secondary air vane positions. Isothermal velocity field measurements in the lower furnace for a given set of vane settings are shown in Figure 3. The velocity vectors represent the two-dimensional flow pattern and mixing schedule in a vertical plane at a burner centerline. The lower flow field is characterized by separating streamlines of looping trajectory with mixing occurring in the area of the furnace centerline. This flow pattern is a result of the meeting and intersection of opposite burner streams. Measurements taken in vertical planes between burners depict the same upward recirculating streamlines but of higher velocity than that shown in Figure 3. The flow patterns determined in this model study conform to the aerodynamic structure of pulverized coal flames observed both in full scale units and in model studies of others[4] on similar furnace configurations.

Although the flow is complex, a simple mixing zone model can be formulated to describe Turbo Furnace mixing patterns. A schematic of a simple two dimensional model is shown in Figure 4. Several recirculation and mixing zones are depicted. A portion of the secondary air flow is seen to enter a final mixing zone above the burners. The amount of this secondary air separation can be controlled with directional vane settings.

EFFECT OF BURNER/FURNACE VARIABLES ON NO_X

Multiple regression analysis was performed on the data sample to determine the influence of various operating and design parameters on the level of total NO_X emissions. In all cases the overall stoichiometric ratio, SR, is found to be the single most important independent variable affecting the results. The burning area heat release, BAHR, is determined as the second principal factor. As indicated in a previous Riley presentation[5], the BAHR is defined as the gross heat input to the furnace, divided by the surface area available for cooling the primary flame to below the point where thermal NO_X fixation reactions are quenched. This approach essentially utilizes the heat release rate as a measure of furnace flame temperature.

Regression results correlating NO_X emissions with SR and BAHR at similar directional air vane settings are shown in Figure 5. NO_X emissions are expressed in ppm by dry volume and adjusted to a common sample dilution of 3% oxygen. The correlation includes test data from all four units tested at various load conditions. These tests covered an excess air range of $1.15 \leq SR \leq 1.54$. None of the units operated under staged or of off-stoichiometric firing conditions.

Linear regression analysis is found to produce the best overall fit to the test data. The results indicate a decrease in NO_X as both excess air and the heat release rate decrease. The standard error of estimate for this relatively simple correlation is 33 ppm.

FUEL NITROGEN EFFECTS

The data sample includes results for three different coal types. These coal types include eastern high volatile A bituminous coals (two units), a mid-western high sulfur high volatile A bituminous coal and a western sub-bituminous B coal.

Adding fuel nitrogen as an independent variable to the regression analysis does not improve the correlation fit and fails to explain the remaining scatter in the data. Fuel nitrogen regression coefficients when added to the correlation function also fail to pass a comparative significance test. Figure 6 is a plot of all NO_X emission data available from this study related to the fuel nitrogen content. Both a bi-variate correlation analysis and a least squares fit through the entire data sample imply a weak and even slightly inverse relationship between these two variables. NO_X emissions for the low nitrogen sub-bituminous coal are in the same range as those for bituminous coals of higher nitrogen content. The results seem to confirm the observations of others[3, 6] that NO_X emissions cannot be cor-

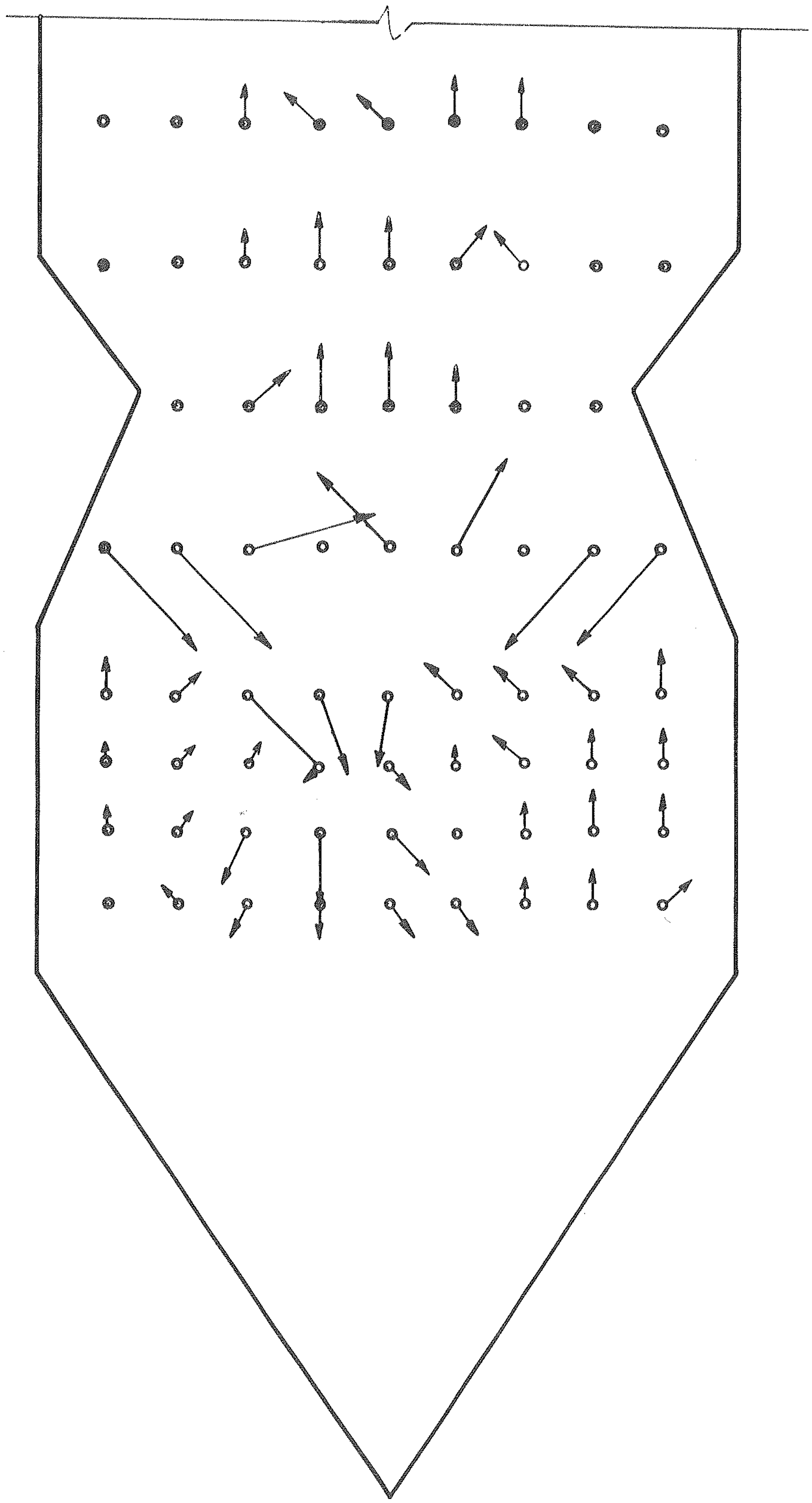

Figure 3 Lower Dry Bottom Turbo Furnace Velocity Field

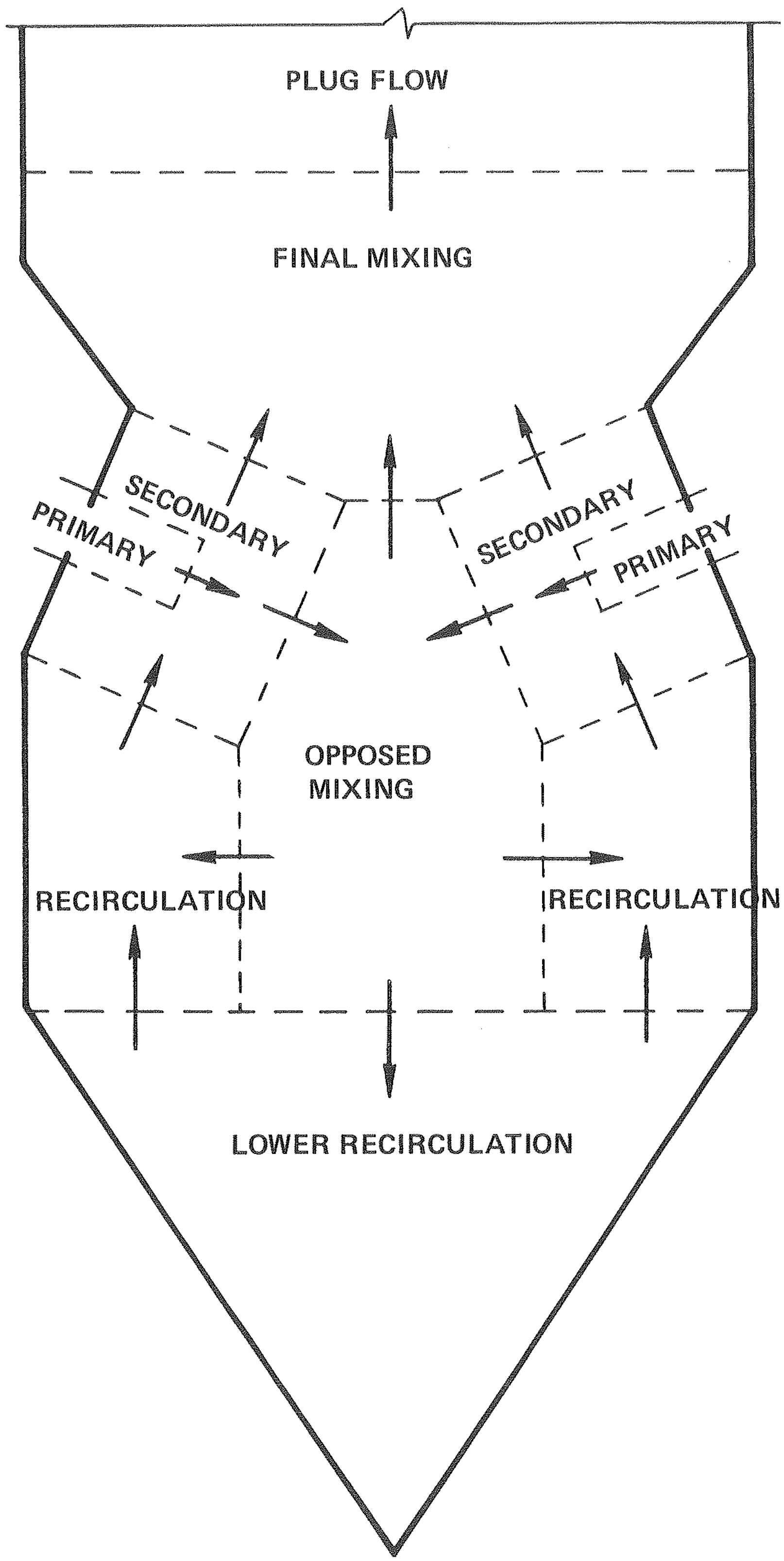

Figure 4 A Simple Turbo Furnace Mixing Zone Model

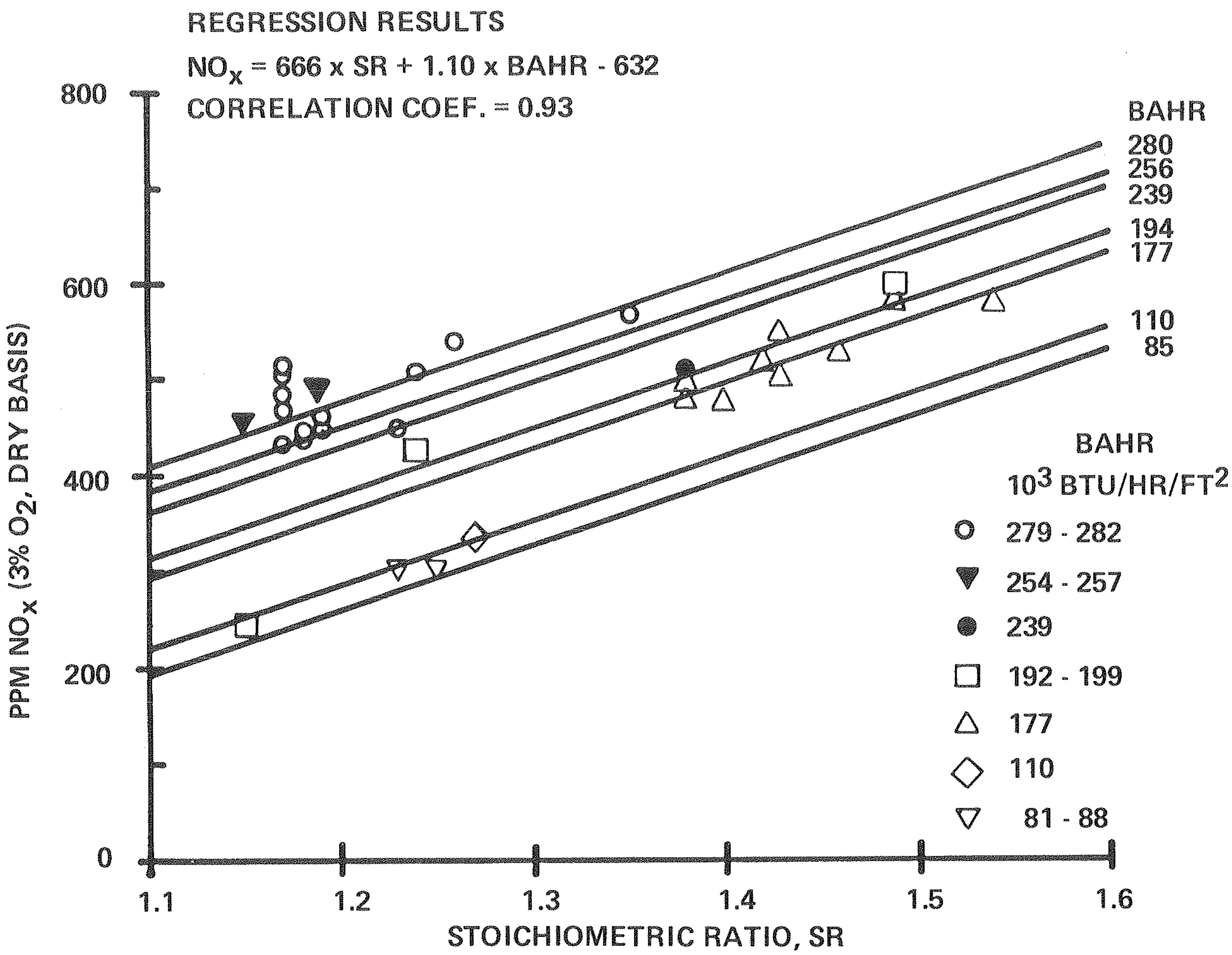

Figure 5 Correlation of NO_x Emissions with Stoichiometric ratio and Burning Area Heat Release

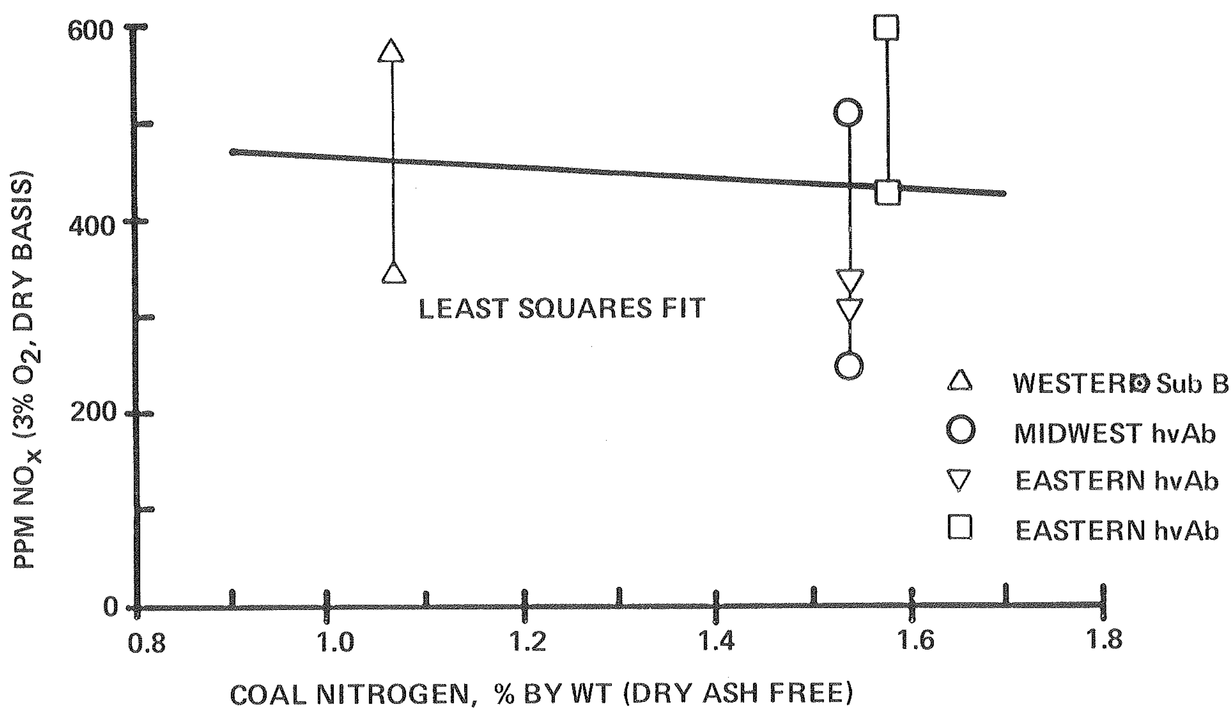

Figure 6 Effect of Coal Nitrogen on NO_x

related with fuel nitrogen alone and that the conversion efficiency of fuel nitrogen to NO_X is inversely proportional to the weight percent of nitrogen in the coal.

SECONDARY AIR MIXING

The effect of the schedule of secondary air mixing on overall NO_X emissions is most clearly seen by examining the results for a single unit firing western sub-bituminous coal. Regression results for this data set are shown in Figure 7. The effect of aerodynamic changes in the flame structure are included along with excess air and heat release rate. The lower lines represent the optimum secondary air vane position which produces the minimum NO_X flame conditions while the upper lines represent the non-optimum case. Directional vane positions which direct a portion of the secondary air to the final mixing zone above the burners, as well as to the lower mixing and recirculation zones, are seen to produce lower NO_X emissions. These mixing zones have been identified previously in Figure 4.

As in the case of the previous regression results, the stoichiometric ratio, SR, is again the process variable which contributes most to the overall fit for each of the correlation functions shown. This data set includes excess air levels in the range $1.13 \leq SR \leq 1.54$.

FUEL NO_X MODEL

In order to aid and extend the interpretation of such parametric analysis a fuel nitrogen conversion model is often utilized. We have found that a simple fuel NO_X model of the form

$$NO_{X_{fuel}} = (a \times SR\text{-}b)\,(N^{1/c}),$$

where N is the fuel nitrogen content on a dry ash free basis and a, b, and c are constants, whose values are greater than unity, provides the most success when applied to our data sample. The fractional exponent for fuel nitrogen results from an assumed inverse relationship between conversion efficiency and nitrogen content.

Correlations resulting from the use of this model, however, do not explain the variation in total NO_X emissions quite as well as the multiple regression results described earlier. The conversion of fuel nitrogen to NO_X is obviously dependent on local oxygen concentrations in the early stages of the flame. The overall stoichiometry as measured by SR provides only a first order estimate of these conditions. More data, therefore, identifying local oxygen concentrations and temperatures are required in order to improve this model.

SUMMARY

Total NO_X emissions in a dry bottom Turbo Furnace are strongly dependent on the overall stoichiometry and can be expressed as a linear function of the stoichiometric ratio. Data analysis reveals an extremely weak correlation between total NO_X emissions and the both fuel nitrogen content and fuel rank. The results suggest that fuel NO_X cannot be correlated with fuel nitrogen content alone. The overall excess air level provides a first order estimate of local flame conditions. Finally, burner directional vane settings can be used to control the schedule of secondary air mixing in the dry bottom Turbo design in order to reduce NO_X emissions.

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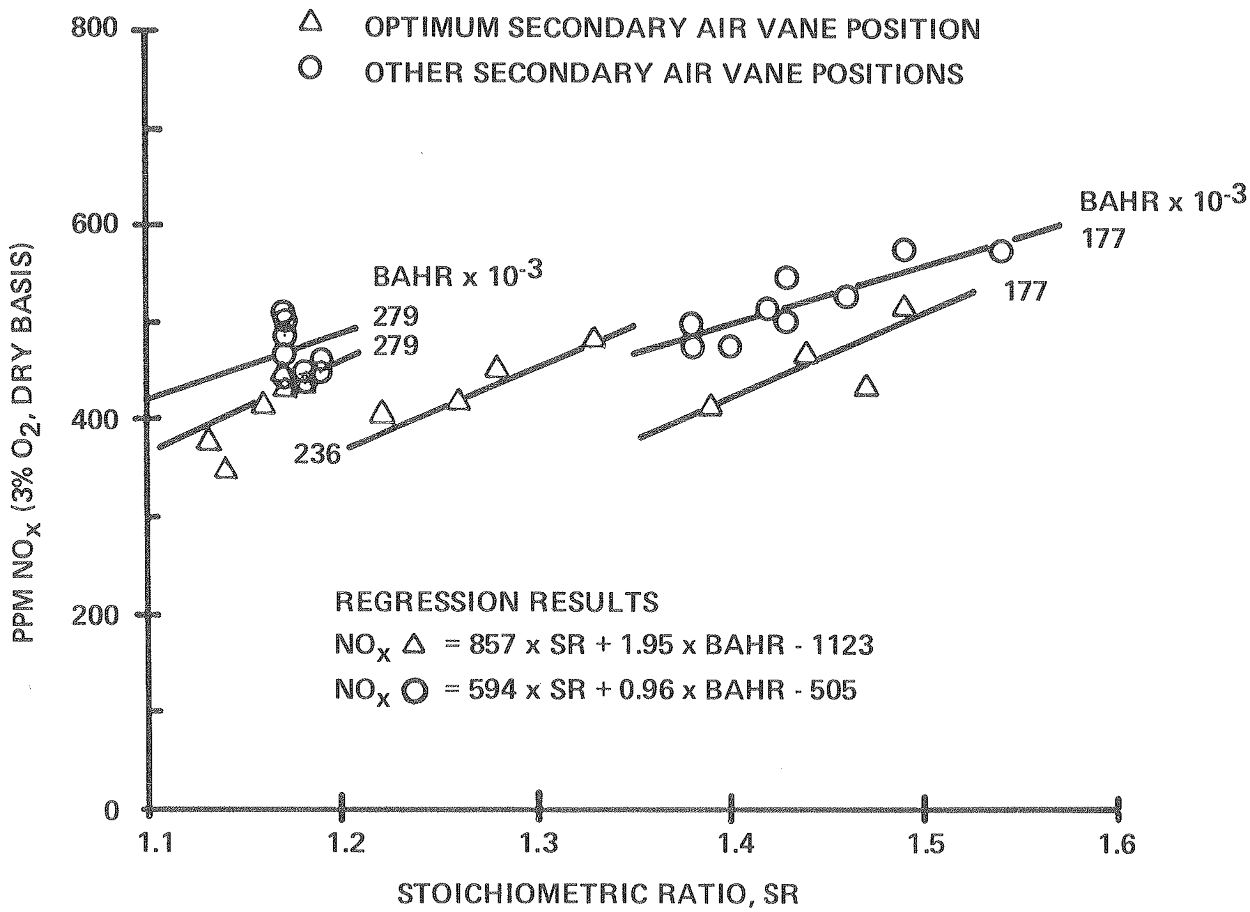

Figure 7 Effect of Secondary Air Vane Position for a Single Unit Firing Western Sub-Bituminous Coal

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