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Project Summary

Burner Criteria for NO_X Control Volume II. Heavy-Oil and Coal-Fired Furnaces and the Evaluation of Radiative Heat Transfer Models

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This report describes Phase II of a research program, the overall objective of which was to specify burner design criteria for minimum pollutant emissions from both pulverized-coal- and residual-fuel-oil-fired combustors. Phase II, included both furnace investigations and the evaluation of radiative heat transfer models which could later be applied to the development of an analytical tool capable of predicting combustor performance; the models helped generalize the results of the furnace experiments.

The furnace investigation had three major objectives: providing further information on NO_x formation in pulverized coal flames; extending the furnace investigations to include fuel oils; and identifying methods of satisfying combustor process requirements while minimizing NO_x emissions through burner designs. Results presented show the emission characteristics of a subscale practical burner, and the development of a tertiary air injection system to minimize NO_x formation by using outboard staged air ports. Emissions from dual-fuel systems were investigated by firing both natural gas and coal simultaneously. Emissions from heavy fuel oil were found to be most dependent on the method of atomization; in general, the lowest emissions were produced from the narrowest spray angles.

The report describes the development of several radiative heat transfer models and compares their predictive capabilities with both experimental results and hypothetical test cases. Three models are described: two-flux models, four-flux models, and a continuous-intensity distribution model (CID). The accuracy of the CID appears to approach that of a zone model, although both complexity and computing times are increased.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Program Overview

This report describes Phase II of a research program whose overall objective was to specify burner design criteria for minimum pollutant emissions from both pulverized-coal- and residual-fuel-oil-fired combustors. Phase I defined the effect of various burner design parameters on the formation of nitrogen oxides (NO_x) in both pulverized coal and natural gas flames. Both input/output investigations and detailed flame mapping were carried out in an attempt to establish flow and mixing patterns which yielded the most promise for controlling NO_x emissions by burner redesign.

The major accomplishment of the Phase I furnace investigations was the demonstration that, under subscale conditions, NO_x emissions from pulverized coal flames could be varied by a factor of four. This variation was achieved mainly by the selection of three burner design parameters:

- The method of fuel injection. Any tendency to mix the coal rapidly with all the combustion air resulted in higher emissions. The lowest emissions were achieved with a high velocity axial fuel injector which maintained a coherent fuel jet of high coal density.
- Optimum level of swirl to provide a stable ignition source at the fuel injector without mixing the fuel too rapidly with the secondary air. Swirl indicates that the secondary air stream has both tangential and axial velocity components.
- The degree of primary air. Primary air is air that is mixed with the pulverized coal prior to delivery into the furnace. NO_x emissions were lowest when the minimum amount of primary air was used consistent with maintaining slow mixing of the fuel jet with the secondary air.

Although burner conditions had been identified which gave low NO_x emissions, it was readily recognized that such a burner design would be unsuitable for use in existing wall-fired utility boilers.

The Phase II furnace trials were planned to achieve three major goals:

- To provide further information on the formation of NO_x in pulverized coal flames to aid in interpreting the results.
- To include residual fuel oil firing, to define parameters that give minimum emissions.
- To investigate methods of satisfying process requirements and produce minimum emissions. This involves defining the combustion requirements of practical systems, as well as attempting to reduce emissions by modifying the burner design.

In addition to the furnace investigations, a parallel effort was to be conducted throughout the entire program to aid in developing an analytical tool which would allow the extrapolation of the experimental results to furnaces and conditions other than those investigated.

Recognizing the futility of attempting to develop a completely predictive model for nitric oxide (NO) formation for the types of flames investigated in the experimental sections of the program, a program of model development was initiated which would provide the components of a modular model. This empirical model would consist of three components:

- Subscale physical modeling to allow flow field and mixing patterns to be assessed, which would be part of the final phase of the program.
- A heat transfer model which, when combined with the heat release profiles calculated from the above, would enable the temperature field to be calculated (described in this report).
- A multiple reactor model which would combine information generated by the first two components, a suitable kinetic mechanism and a minimum number of adjustable empirical constants to predict pollutant formation which could be constructed when an adequate kinetic mechanism was available.

This model would be used to predict trends associated with such parameters as injector type, extremes of swirl level, and fuel type. Although it would not be possible to combine the physical and heat transfer models with a suitable reactor model in this program, the satisfactory separate operation of either component would represent a significant contribution. In Phase II, several radiant heat transfer models were developed and evaluated.

Furnace Investigations

The furnace investigations covered a wide range of topics, some of them exploratory or diagnostic, and others concerned with an assessment of burner parameters capable of providing combustion conditions suitable for practical situations, and yet with minimum pollutant emission characteristics. The experimental investigations were carried out in a partially cooled refractory tunnel furnace with three fuels: natural gas, a residual fuel oil of 0.24 percent nitrogen, and a bituminous coal of 1.05 percent nitrogen content. The trials, conducted over a 6-week period, emphasized five areas:

- Determining the emission characteristics of a subscale practical burner to permit comparisons with the moving-block swirl burner used exclusively during Phase I.
- Developing a burner with a tertiary air supply to produce low NO_x flames which satisfy practical requirements.
- Investigating the emission characteristics of flames produced by simultaneously firing pulverized coal and natural gas.
- Establishing the influence of various burner design parameters of pollutant emissions from residual oil flames.
- Comparing the influence of air preheat on NO_x formation from natural gas, residual fuel oil, and pulverized coal.

The most significant results follow.

Emission Characteristics of a Subscale Practical Burner

Results obtained in the International Flame Research Foundation tunnel furnace, were similar to those reported in 1975 (EPA-650/2-74-002b). NO_x emissions increased with increasing excess air, although the precise influence of preheat, excess air, and firing rate were not duplicated. Very high NO levels (in excess of 1700 ppm) were recorded at high firing rates and 450°C preheat with an almost uncooled furnace. These high emissions are probably due to an increasing contribution of thermal NO and to more complete loss of nitrogen from the coal char because of the higher temperatures.

Figure 1 shows how emissions from the subscale burner could be modified by changing the method of fuel injection and the amount of air supplied with the coal in the primary stream. Reducing the tendency of the coal jet to spread and mix rapidly with the combustion air reduces emissions by more than 28 percent for a given set of input conditions.

Tertiary Air Injection to Reduce NO_x Formation

The total combustion air supply was divided into three streams to delay the mixing of the fuel with all the air by injecting one of these streams (tertiary air) from the periphery of the burner. In the most successful application of the technique (Figure 2), 40 percent reductions in emissions from the subscale practical burner were achieved with 20 percent of the stoichiometric air requirement supplied in the tertiary stream. Incorrect designs caused 300 percent increase

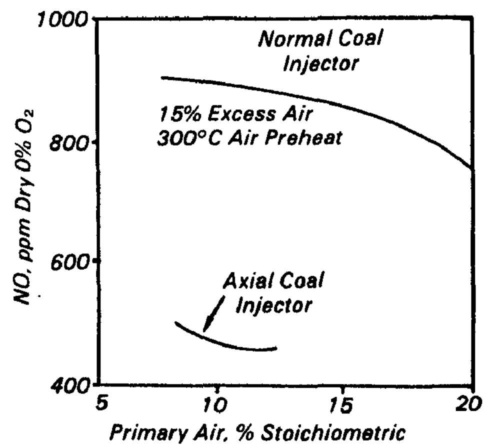

Figure 1. *Emission levels from a subscale practical burner can be reduced by modifying the method of fuel injection.*

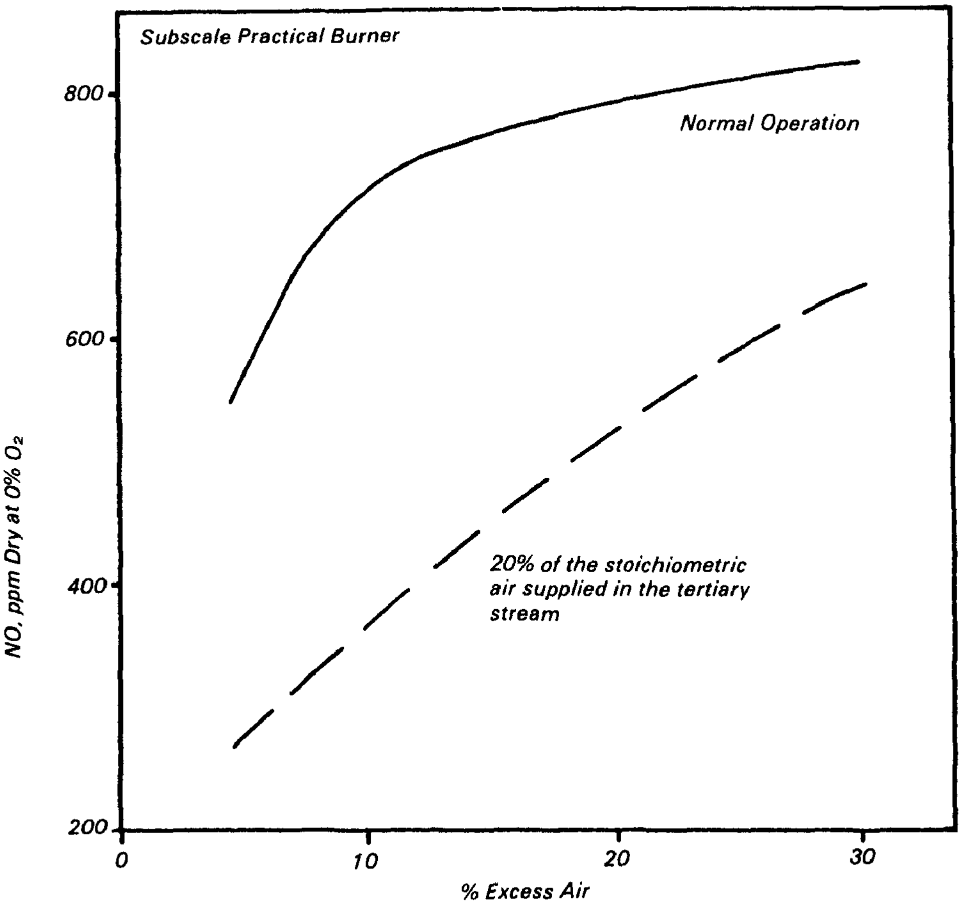

Figure 2. The use of tertiary air injection can reduce NO_x emissions from coal-fired burners by a substantial amount.

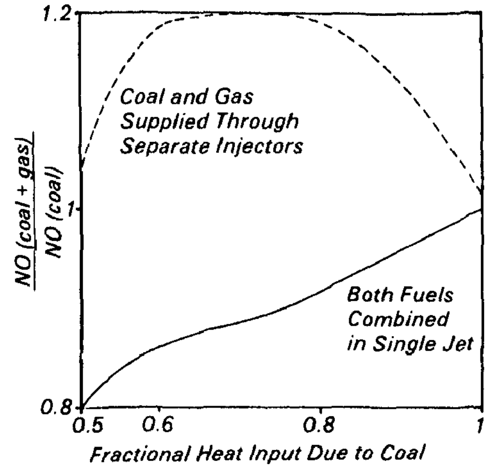

Figure 3. Effect of mixed-fuel firing on NO_x emissions.

in emission from natural-gas-fired tertiary air systems.

Emission Characteristics of Dual-Fuel Systems

NO_x emissions resulting from the simultaneous firing of gaseous and solid fuels are not additive. The emission characteristics of dual-fuel firing depend on such burner parameters as fuel injector type. Figure 3, for a fixed total heat input, shows emissions from simultaneous coal-plus-gas firing as a ratio of emissions with coal alone as a function of the fractional heat input due to coal. The fractional conversion of fuel nitrogen to NO increases with decreasing nitrogen content. Mixing gas and coal reduces the overall nitrogen content of the combined fuel which could partially explain the increased emission due to combined firing. The rate of volatile fuel nitrogen evolution depends on particle heating rate and (therefore) gas temperature, which varies in the early stages of the flame as a result of mixed-fuel firing. The heating rate may also affect char nitrogen content, and the lower emissions from combined firing shown in Figure 3 may be the result of reduced char nitrogen conversion.

Emission Characteristics of Fuel Oil Flames

The emission characteristics of fuel oil containing significant quantities of bound nitrogen appear to follow trends similar to those observed with coal. Lower NO emissions were generally obtained if the fuel spray was narrow. The lowest emissions (about 100 ppm) were obtained with axial fuel oil injection produced with an air blast atomizer. Further work under cold-wall conditions would ensure that low-NO_x conditions do not produce excessive amounts of particulate matter. The further investigation of the influence of thermal effects (air preheat and furnace heat extraction rate) would also be helpful. Figure 4 shows that the influence of air preheat varies with the fuel atomizer design.

Radiative Heat Transfer Models

The ability to calculate radiative exchange within combustion systems is a necessary component of a predictive procedure capable of calculating combustor performance. The various methods of evaluating radiant heat exchange in enclosures were reviewed from several aspects: (1) their accuracy; (2) their computational convenience; (3) their suitability for coupling with elliptic field equations describing flow, mixing, and heat release; and (4) their suitability for combining with the results of physical models to provide a short-term solution. Effort was concentrated on developing flux models because of their suitability for integration with flow field models.

Although the Zone Method of analysis is the most accurate way to evaluate radiant heat exchange under certain well-defined conditions, it was deemed less appropriate for the needs of the total program. Its accuracy is reduced considerably if reasonable restrictions are placed on computer storage and run time where steep temperature and concentration gradients occur and there are wide variations in attenuation coefficients throughout the furnace volume. In general, flux models are less accurate than the Zone Method because of approximations involved in describing intensity distribution at a point. When greater accuracy is required, continuous intensity distribution (CID) models have been developed whose accuracy is comparable to that of the Zone Method, but which require reduced computer requirements. They also have the added advantage that they can be combined easily with prediction procedures for other transfer processes.

The report describes the development of several radiative heat transfer models, and their predictive capabilities have been compared with both experimental results and hypothetical test case results. Comparison with experimental furnace results does not necessarily provide the best method of

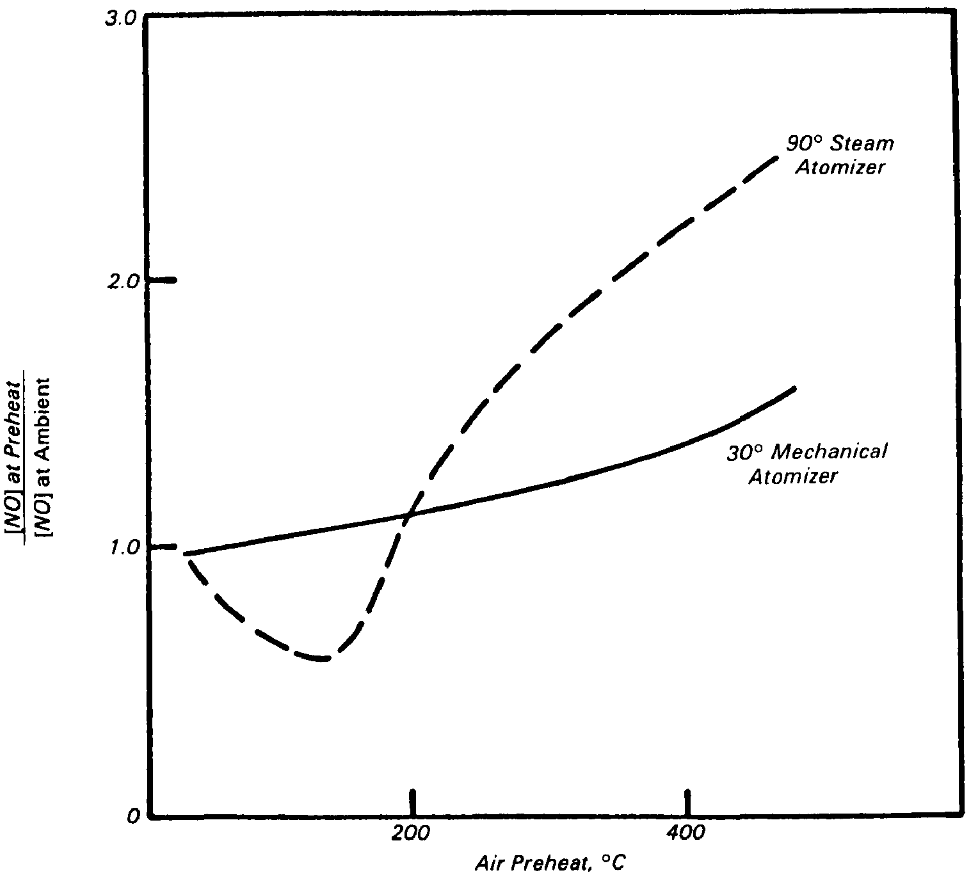

Figure 4. *The effect of air preheat on NO_x emission from residual fuel oil can depend on atomizer design parameters.*

evaluating radiative heat transfer models, since discrepancies between measurement and prediction can be attributed to errors in either calculating radiative exchange or the representation of the emission/absorption/scattering characteristics of the bounding walls and the furnace gases (which may include such solid particles as soot and ash). The following models have been developed and their characteristics evaluated:

- Two-flux models based on Spherical Harmonics and the Discrete Coordinate Method. Both can predict radiative heat transfer to furnace side walls with errors of less than 9 percent in the absence of steep axial gas and wall temperature gradients. Larger errors occur if steep gradients exist, as no account is taken of exchange perpendicular to the main two-flux coordinate direction.
- Four-flux models based on the Discrete Coordinate Method which usually predict with errors of less than 10 percent even though steep axial wall and temperature gradients occur. If the end wall is much cooler than the adjacent gas zone, larger errors can occur close to the cool wall. Only slight errors are introduced into the prediction of total heat transferred because overprediction in certain areas is balanced by underprediction in others.
- A CID model which represents the intensity distribution around a point as a continuous function (the discrete coordinate method assumes that the intensity is constant over a certain solid angle, introducing discontinuities). The accuracy of the CID model appears to approach that of a Zone Model.

Inaccuracies in predicting radiative heat transfer in furnaces may be associated with the representation of the emission/absorption properties of furnace gases. Unidirectional intensity measurements are compared with predictions involving the representation of the real combustion gases as a gray gas, the sum of four gray gases, or the sum of one clear and two gray gases.

Although it cannot be claimed that the one gray gas assumption is accurate, for the circumstances tested, it appears to be equally effective as either of the other approaches if steep concentration and temperature gradients do not exist. If gradients exist, deviations between measured and predicted intensities can increase up to 40 percent. These errors are attributed to the representation of the radiative properties of the gases rather than to that of the wall. An extensive assessment of these errors has not been possible because of a lack of information on the spectral distribution of attenuation coefficients under furnace conditions.

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