SIMULATION & NO_x CORRELATION FOR COAL-FIRED BOILER

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Introduction

Oxides of nitrogen (NO_x) are a major pollutant evolving from combustion processes. Federal emissions regulations are become increasingly stringent, in order to abate harmful NO_x emissions. Some of the proposed NO_x reduction strategies for stationary combustion systems are:

- Combustion modifications
- Reduction technologies (both catalytic and non-catalytic)
- Fuel additives and alternative fuels
- Reburning technologies
- Low-NO_x burners
- Feedback control & monitoring technologies.

Computational Fluid Dynamics (CFD) has been used to simulate combustion for decades. Simulations have been employed to assist in the design of improved burner geometries, the analysis of alternative fuels and reburning conditions, and various other applications. While studies have shown simulated results for NO_x emissions, temperature profiles and flow fields, for given planes within the boiler, no numerical relationships between such data have been determined.

The desire to implement a temperature measurement-based monitoring and feedback control system for improved NO_x control necessitates the discovery of a functional correlation between boiler temperature distributions, boiler operating parameters, and NO_x formation. This numerical simulation effort has the objective of determining how best to implement the temperature profile information that can be obtained with a new fiber optic temperature sensor under development at Penn State University, which can provide a measurement of the temperature distribution along a line-of-site across the interior of a boiler.

The work herein is focused on modeling the "demonstration boiler" at the Energy Institute at PSU. The grid was generated in Gambit 2.1, and a commercial CFD code, FLUENT 6.1, was used for simulation. Tests were designed and data was collected for typical and low-NO_x conditions. Data was collected at several planes within the boiler.

Numerical Modeling Approach

Two different cases were modeled based upon the configuration of the demonstration boiler: a normal case, where primary, secondary and tertiary air flow rates were set at conventional operating conditions; and a low-NOx case, where the secondary air flow rate is decreased and that air flow is redirected to become a tertiary air flow.

Demonstration Boiler. The demonstration boiler, located at Penn State's Energy Institute, is a D-type design watertube boiler, manufactured by Tampella Power Corporation [1].The boiler has approximate dimensions (in meters) of 2.65x1.83x2.59. It is rated for 15,000 lb/h steam (@300 psig), and was initially designed for fuel oil-firing, but has since been modified for coal-based fuels.

The three-dimensional, nonuniform grid of the demonstration boiler is shown in Figure 1. The grid was meshed at a spacing of 3, and comprises nearly 273,000 nodes.

Numerical Model. The solutions were obtained using an implicit, segregated solver, for non-premixed, steady state combustion. The k-ε model was employed as the turbulence model for this work, which is widely used combustion modeling [2].

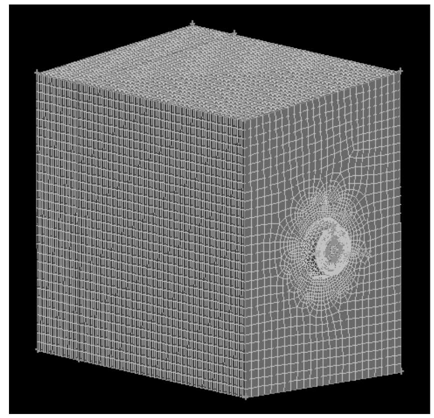

Figure 1. Three-dimensional demonstration boiler grid

The turbulent intensity is a function of the upstream flow conditions. The mixture fraction/PDF formulation, which was developed specifically to model turbulent diffusion flames [3], was used to model the combusting flow, along with the P-1 radiation model and NO_x postprocessor. Chemical equilibrium relates instantaneous mass fractions and temperature with the mixture fraction. The P-1 radiation model is advantageous due to its simple diffusion equation, which allows particulate scattering [4] and requires low CPU demand. The mixture fraction method permits intermediates, dissociation effects, and coupling between turbulence and chemistry to be accurately accounted for. A probability density function (PDF) accounts for the interaction of turbulence and chemistry [3], simulating realistic finite chemistry in turbulent flames. The density-weighted time-averaged Navier Stokes equations are solved for temperature, velocity, species concentrations and variance, from which the time-averaged NO formation rate is computed at each point, using the averaged flow-field information [3, 5]. Since the rate of NO_x formation is sensitive to temperature, the combustion solution must be highly accurate to attain reasonable results.

A Rosin-Rammler distribution was assumed for the coal particle size distribution. The particles were injected at four positions, for a total mass flow rate of coal of 0.37 kg/s. The air was injected according to Table 1.

Solutions are calculated based on the conservation equations. The continuity equation is:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \qquad (1)$$

The turbulent flow conservation equations for momentum and energy are as follows, respectively:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho h_t)+\frac{\partial}{\partial x_j}(\rho u_j h_t)=\frac{\partial p}{\partial t}+\frac{\partial}{\partial x_j}(u_i\tau_{ij}-q_i) \quad (3)$$

Table 1. Inlet and Outlet Conditions for Both Cases

	Normal	Low-NO_x
Inlet Conditions		
Primary Air Flow Rate (kg/s)	0.2	0.20
Secondary Air Flow Rate (kg/s)	0.53	0.76
Tertiary Air Flow Rate (kg/s)	1.23	1.00
Fuel Flow Rate (kg/s)	0.37	0.37
Outlet Conditions		
Area Weighted Ave. T (K)	1712.72	1456.16
Area weighted Ave. NOx (ppm)	397.31	283.81

Results & Discussion

Calculations were performed for the conventional and low-NOx cases, from which temperature and NOx distributions were generated.

Figure 2 and **Figure 3** portray various temperature gradients over the specified surfaces. At conventional operating conditions, the elevated temperatures are indicative of coal particles trapped in recirculating flow regions, depleting available oxygen, and hence yielding significant NOx formation with adequate residence time. In the low-NOx case with air-staging, high temperature zones are fuel-rich and therefore lead to higher CO production. Though the temperature and residence time may be conducive to NOx formation, the depleted oxygen reduces net NOx formation. Successful air staging provides significant stratification of the combustion process, and thermal non-uniformity, as shown in the low-NOx case temperature profile, which indicates the extent of stratification.

Statistical Analysis. Data, in the form of 1D "lines" of information (simulating the data to be collected from the fiber-optic sensor, spanning the boiler), resulting from CFD calculations will be analyzed statistically in order to determine a correlation.

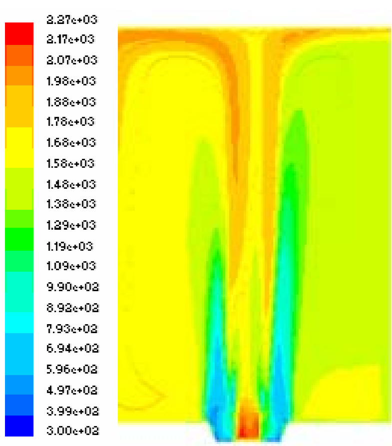

Figure 2. Low-NOx case temperature profile (axial surface)

Regression studies will be employed for the conventional and low-NOx cases. A series of regressions will be performed for each scenario, with NOx concentration held as the response variable, while predictor variables comprise T, velocities and other stoichiometric parameters in various combinations. The combination providing the best (highest) R-squared value for each case will be accepted and used in a regression study comparing the two cases.

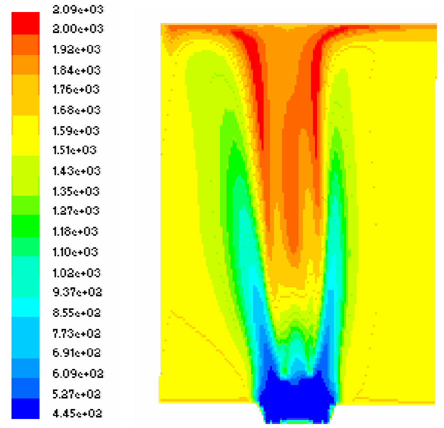

Figure 3. Conventional case temperature profile (axial surface)

Conclusions

Two separate calculations were performed with secondary and tertiary air flow rates as the only variables. The temperature profiles presented for each case provide evidence that data from a one dimensional sensor spanning a boiler in strategic locations may provide pertinent information to allow real-time NOx control.

Temperature, NOx concentrations and velocity profiles were collected for specified planes within the boiler. These parameters will be compared against one another via statistical analysis, in order to determine an algorithm for implementation in a NOx control system, in conjunction with a fiberoptic, in-situ temperature sensor.

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