Effects of Swirling Flow on Nitrogen Oxide Concentration in Pulverized Coal Combustors

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Introduction

Nitrogen-containing pollutants from pulverized coal conversion processes have been of concern for several years, and reviews of this subject have been published (Wendt, 1980; Chen et al., 1981). Swirl of the secondary stream is one technique of

Wendt, 1979). In other cases, increased swirl initially decreases NO emissions (Harding et al., 1982; Asay et al., 1983). Thus, the observed effects of swirl are varied, and indicate that additional parameters influence the NO emissions. In this note a model, described in detail elsewhere (Smith and Smoot, 1981; Smith et al., 1981, 1982; Hill et al., 1984), was used for interpreting effects of inlet stream swirl and velocity on NO emissions during combustion of pulverized coal.

The model incorporates a simplified kinetic mechanism, combined with effects of the turbulence. The pollutant species equations are decoupled from the overall velocity, temperature, and major species field equations. The equation set was presented by Smith et al. (1982). Fuel nitrogen is assumed to evolve from the coal at a rate proportional to coal weight loss, with instantaneous, quantitative conversion of the fuel-N released from the coal to HCN, during coal devolatilization and heterogeneous char reaction. NO then forms from oxidation of HCN. HCN also reacts with the NO to form N_2. Global kinetic rates of reaction of gaseous HCN with both oxygen and NO were taken from DeSoete (1975). Thermal and prompt NO formation is neglected. Heterogeneous NO reduction is modeled by a slower (nonfluctuating) reaction using the kinetics of Levy et al. (1981). The reaction sequence is:

Coal(fuel – N) →

O_2 char

NO → N_2

To account for turbulence effects, gaseous reaction rates are assumed to be functions only of the local, instantaneous stoichiometric ratio at each location in the reactor. This assumption is based on some experimental observations in gas systems (Bilger, 1978; Fenimore and Fraenkel, 1981). The model does not require that the relationship between the species mass fraction and the stoichiometric ratio be unique for the whole flow field, and thus the reaction times may be different throughout the reactor. The time-mean reaction rates are obtained by assuming that the species mass fractions are locally linear functions of stoichiometry, and then integrating the resulting kinetic expressions over the probability density functions for the appropriate mixture fractions. The pollutant concentrations are obtained by solution of the time-averaged species continuity equations. The NO model is less applicable to fuel-lean systems where thermal NO cannot be rejected. The coal combustion code used with the NO model was developed previously, and is referred to as PCGC-2 (pulverized coal gasification and combustion: 2-dimensional). Fletcher (1983) and Sloan (1985) show extensive evaluations of this coal combustion model by comparison with experimental data.

Computations are made for a vertical, cylindrical, down-fired laboratory combustor, described in detail by Asay et al. (1983). Major parameters used for the predictions are: subbituminous

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coal, swirl number = 2.0 (except where otherwise indicated); stoichiometric ratio (SR) = 1.06; coal feed rate = 13.6 kg/h; primary air feed rate = 25.3 kg/h; secondary air feed rate = 69.6 kg/h; primary and secondary stream temperatures = 300 and 590 K, respectively; primary and secondary stream diameters = 2.2 and 9.4 cm, respectively (except where otherwise indicated); reactor length and I.D. = 1.57 and 0.20 m, respectively; wall temperature = 1,000 K.

Secondary Stream Swirl Number

PCGC-2, coupled with the NO model was used to investigate conflicting observations of swirl level and flow velocity on NO emissions. Figure 1 shows a comparison of predicted and measured NO concentrations as a function of secondary stream swirl number for the subbituminous coal (Asay et al., 1983). The predictions are revised from those of Hill et al. (1984). The swirl number is a measure of the angular momentum imparted to the inlet streams, and is defined as: S = (flux of angular momentum/flux of axial momentum × burner radius). The predicted and observed results show a similar trend, even though predicted values are only bracketed by the measured data. The minimum NO emissions occurred at a swirl number of about 2–3 for this case.

Other predictions of the effect of swirl on NO emissions are shown in Figure 2. The conditions for Figure 2 were the same as shown in Figure 1, except for the velocities, and thus flow areas, of the primary and secondary streams. In Figure 2, curve A, the primary stream velocity is five times lower while the secondary stream velocity is twice that of Figure 1. In Figure 2, curve B, the primary velocity is five times higher while the secondary stream velocity is the same as that of Figure 1. For the lower primary velocity case (Figure 2 curve A), NO emissions increased and then flattened with increasing swirl number. This trend is the opposite of that shown in Figure 1, but has been observed by the investigators cited previously. For the higher primary velocity case (Figure 2 curve B), the decrease in NO emissions with increasing swirl number is even more dramatic than for the conditions of Figure 1. These differences indicate that the relative momenta of the swirling secondary air stream and primary coal-air stream influence the ignition process, the

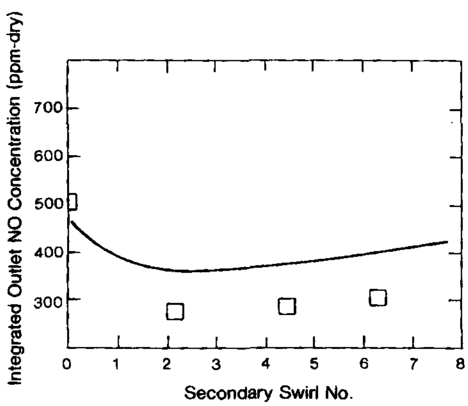

Figure 1. Comparison of outlet concentrations of NO (ppm-dry) in a laboratory furnace for a subbituminous coal as a function of secondary stream swirl number from model predictions (___) and measurements (□).

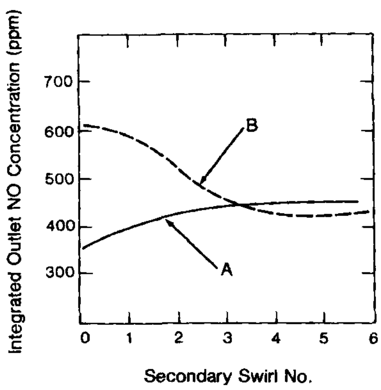

Figure 2. Comparison of predicted NO (ppm-dry) concentrations in a laboratory furnace for mean primary velocities of A: 3 m/s (___) and B: 75 m/s (--). All other conditions are the same as in Figure 1, primary velocity of 15 m/s.

extent to which these streams mix, and the subsequent amount of NO formed.

For sufficiently high primary velocities associated with Figure 1 and Figure 2 curve B), the primary stream initially withstands the swirling secondary flow, and the streams mix at their interface only enough to attach the flame to the burner. The unmixed portion of the secondary stream is in an annular region around the coal-laden primary stream. At low swirl numbers, there is not enough shear between the two streams to provide rapid complete mixing, resulting in a fuel-rich central core. The coal reserves enough radiation from the surrounding reaction zone to promote devolatilization and reaction in this fuel-rich environment. As the swirl level increases, the mixing rate of these streams is enhanced. This increases contact of the volatiles and oxygen, and subsequently increases NO formation. For the lower primary velocities associated with Figure 2 curve A, mixing of the oxygen with the primary jet occurs more completely in the forward region near the burner, and any increase in swirl number only enhances mixing of the primary and secondary streams. This increased O_2 penetration increases NO formation.

Primary Stream Diameter

Since the effects of swirl are linked to the feed stream velocities, the separate effects of primary stream velocity were briefly explored. For a constant mass flow rate, the primary stream velocity is inversely proportional to the square of the diameter. For these predictions, the same cross-sectional area of the secondary stream inlet was used to maintain the velocity and mass flow rate of the secondary air. Figure 3 shows that as the primary stream diameter is increased (primary velocity decreased), NO emissions first decrease, and then increase. At the same time, coal burnout decreases only slightly at first, and then remains constant at 80%.

Heap et al. (1973a) measured the effects of primary velocity on NO emissions for various secondary stream swirl levels. These measurements show that NO emissions can increase or decrease with increased primary velocity, depending on the secondary swirl level. These tests were conducted in a horizontal, rectangular system, and the average primary velocity was varied

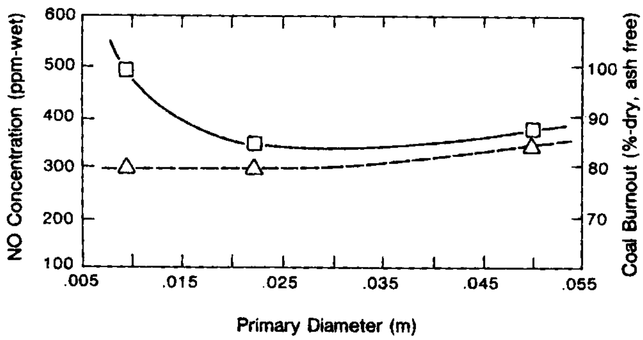

Figure 3. Effect of primary stream diameter (and thus primary stream velocity) on predicted NO concentration (ppm-wet) and coal particle burnout (% dry, ash-free) where swirl No. = 2.0. All other conditions are the same as in Figures 1 and 2.

from 19–52 m/s. The lowest primary velocity resulted in the highest NO emissions at all swirl numbers (all higher than for predictions in Figure 3). However, at some swirl levels the highest primary velocity resulted in considerably higher NO emissions than did the intermediate primary velocity (26 m/s). Here, NO first decreased and then increased with primary velocity as the swirl was increased.

Harding et al. (1982) observed that primary velocity had only a small impact on NO emissions. These tests were from a laboratory-scale combustor, and the primary velocity was reduced from 30 to 15 m/s. The effect of primary velocity was also shown to be a function of swirl number and stoichiometric ratio, and the effect of primary velocity on NO emissions increased with increasing stoichiometric ratio. Wendt and Pershing (1977) observed that NO emissions first decreased and then increased as the primary velocity was increased. These tests were conducted with a laboratory-scale diffusion flame where the primary velocity was varied from 20–100 m/s by changing the percentage of stoichiometric air in the primary stream. A dramatic increase in NO emissions was observed when the primary velocity caused the flame to lift from the burner.

Discussion

Concentrations of NO at the exhaust of coal combustion furnaces are strongly dependent on local conditions early in the combustion process. Integrating the effect of the turbulence and the chemical reaction rate processes has allowed predictions to be made which compare favorably with measurements. Previous apparent contradictory observations with respect to the effect of swirl number on NO emissions have been explained with the model. Outlet NO concentrations increase or decrease with increasing swirl number, depending on the local mixing and reaction processes in the core of the developing jet near the burner exit.

Acknowledgment

The authors acknowledge the assistance of Lynda Richmond and Shane Olsen in preparing the manuscript and illustrations.

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Manuscript received Nov. 28, 1984, and revision received Mar. 20, 1986.