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# Parametric study of combined premixed and non-premixed flame coal burner

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## Abstract

A combined gas/air mixture–coal burner was developed to include heat recirculation by utilizing a radiative solid material with premixed flame jets impinging onto the downstream side to preheat the fuel/air jet on the upstream side. Providing the heat recirculation mechanism at different air staging degrees enhanced the destruction rates of the fuel nitrogen oxides. Concentric elliptical premixed gas/air and coal/air jets had a stronger preheating effect and a consequent increased $NO_x$ reduction effectiveness as compared to concentric circular jets, where the inner elliptical jets enlarged the contact diffusion area and entrainment thus increasing the preheating time. The parametric variation in the feeding ports to the coal combustor affected the exhaust emissions, wherein the use of an inclined or shifted injection from the centre-line contributed to the $NO_x$ reduction. Increasing the jet angle in the upstream direction reduced the CO concentrations, while the $NO_x$ emissions varied depending on the degree of staging. The inverse/normal flame configuration was found more effective than the normal flame configuration with respect to $NO_x$ reduction that was enhanced at higher heat input ratios. Utilizing inverse triple flames led to a further $NO_x$ reduction since higher temperatures prevailed in the initial flame region with a five reaction zone structure. Finer particles produced less $NO_x$, which was further reduced by blending the coal with biomass.


*Keywords:* Combustion; Premixed; Non-premixed

## 1. Introduction

There is a strong and continuous demand to reduce $NO_x$ emissions from pulverized coal-fired boilers [1], where it is said that 80–90% of the total NOx is attributed to the fuel $NO_x$ [2]. Numerous techniques have been developed to reduce $NO_x$ emissions from coal-fired power plants by combustion modifications such as reduced flame temperatures, air and fuel staging [3], and catalytic combustion [4]. Jones et al. [5] reported some other techniques, including flue gas recirculation and ammonia injection into the flue gas, so that nitrogen oxides are reduced to $N_2$ harmless nitrogen.

On the other hand, other routes may be enforced for $NO_x$ reduction by controlling the overall mechanisms of $NO_x$ formation from either char or volatiles. Regarding $NO_x$ formed from volatiles, the particle temperature was found to have a considerable influence. In this case, the volatile yield and nitrogen release are quite sensitive to the heating conditions, where the volatile amount under rapid heating is somewhat larger than the proximate volatile matter [6]. Bool and Kobayashi [7] stated that since the reaction rates driving $NO_x$ and fuel nitrogen species to $N_2$ are strongly dependent on temperature and residence time, there should be a compromise between creating a fuel rich zone and burning enough fuel to maintain a high flame temperature. They used oxygen as a fuel oxidizer to increase the flame temperature so that the devolatization rates increased. The higher volatile yield with the increased gas-phase combustibles thus created more favorable rich fuel conditions to inhibit $NO_x$ formation from volatiles. The higher devolatization rates also led to less residual carbon issuing from the burner attached zone with a

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consequent reduction in the char $NO_x$ and exhausted carbon [8].

The flame location was found to have a profound mutual effect on $NO_x$ emissions. Enhancing the volatile yield increases the flame radius (for homogenous reaction), thus delays the oxygen penetration to the char with a subsequent reduction in the char $NO_x$ [9]. These characteristics were revealed by Wendt [10], where the inter-particle interactions were said to influence the coal particle burning mechanism in such a way that the volatiles burn either in jets or as an envelope flame which may prevent oxygen from reaching the particle surface [11]. On the other hand, the flame stays closer to the surface by increasing the free stream temperature so that the homogenous combustion mode changes to heterogeneous. The greater energy feedback from closer flames hence increases the particle heating rate and reduces the devolatization time, where the fuel nitrogen species are converted to $N_2$ in a reducing environment within a compact furnace length. In this case, gases devolatize from the coal ignite and react directly with the primary air. If the oxygen in the primary air stream is consumed by nitrogen-free volatiles and if some nitrogen is evolved with such a paucity of oxygen, then there is a possibility whereby fuel–N pyrolyzes to form $N_2$ [10]. Any earlier oxygen contact with nitrogenous species should be avoided to minimize oxidation to $NO_x$.

It is thus concluded that controlling the initial coal combustion stage by increasing the heating rate may contribute to the $NO_x$ destruction in the burner region, while the overall $NO_x$ control can be aided by one of the other known techniques such as air staging. Such combined $NO_x$ control is proposed in the current work to enhance the performance of conventional air-staged coal combustors. The shortages of using only conventional air staging can be inferred by considering that devolatization is a fast process on the relative scale (requiring an order of 0.1 s) as compared to the subsequent heterogeneous char combustion (with an order of 1.0 s). With higher burning capacities required in air-staged low $NO_x$ burners, combustion generated pollutants cannot be still maintained at their respective reduced levels. In such cases with residence times in the reducing zone of at most a few milliseconds, the coal particles may not have achieved their asymptotic nitrogen yield upon leaving the reducing zone and starting combustion with the secondary air. Also, the conventional air-staging involves lower combustion intensities.

The optimum way is thus to increase the initial temperatures and in the same time remove oxygen from the region around the coal particles, which is best achieved by employing a premixed flame in the vicinity of the coal burning zone. The incorporation of a premixed flame in a staged air combustor is thus commissioned to increase the combustion intensity and to provide initial high temperatures with fuel rich conditions necessary for $NO_x$ destruction. Once the mixture is ignited, the temperature increase is associated with oxygen disappearance such that the $NO_x$ is converted to $N_2$ through the respective reduction mechanism having been accelerated by the elevated temperatures [12].

When coal combustion is combined with a premixed flame, the $NO_x$ reduction rates increase in the rich fuel zone as the coal particles are preheated in a reducing atmosphere. Furthermore, the post-premixed flame gas temperatures decrease by the coal utilized as a strongly radiative medium thus the driving forces for $NO_x$ generation from the premixed flame are reduced. In the case if the premixed and non-premixed flames are separated by a distance, a block of solid radiators may be utilized to convey the premixed flame released energy to the coal flame region, so that a preheating effect is obtained. The premixed flames impinge on each other and on the downward face of the solid matrix with a subsequent turbulence generation and enhanced heat transfer [13]. Therefore, the enhanced gaseous mixture flame speed sustains higher burning flow rates, with a subsequent reduction in the residence time for $NO_x$ formation. On the other hand, the heat recirculation to the coal provides higher temperatures in the absence of air thus increasing the pyrolysis rates for $NO_x$ reduction. This represents an advantage over conventional staged combustors, which usually have residual unburned carbon as temperatures in both primary and secondary stages are reduced due to coal radiation.

The role of heat recirculation from the premixed flame to the coal flame in $NO_x$ reduction is thus revealed. The heat recirculation ratio and air staging intensity are modulated for optimum combustion performance. At lower staging intensities, the thermal $NO_x$ is reduced by the shorter residence times at higher flow velocities across the combustion primary zone. On the other hand, at higher staging degrees, the aerodynamic flow parameters may be modulated to increase the residence time in the $NO_x$ -reducing environment [14]. The currently investigated aerodynamic parameters include the off-axis and the inclined injection toward the burner upstream side. Furthermore, other geometrical and aerodynamic effects are studied by varying the combustibles' concentric port design to blend the two flames more effectively such that the elliptical jet favourable characteristics are addressed. The kinetic effects on $NO_x$ emissions are also highlighted by comparing normal, inverse/normal and triple flame configurations. An enhanced $NO_x$ emission control is thus proposed in the current work.

The co-firing of natural gas and coal in a blending or a subsequent burning fashion is recently considered an efficient tool for $NO_x$ reduction. However, the employment of interacting premixed gas and non-premixed coal combustion has not been addressed so far. The parametric variation is also still required to fully highlight the characteristics of such low $NO_x$ burners. Bar-Ziv et al. [15] investigated $NO_x$ reduction by coal/natural gas reburning to reduce the coal $NO_x$ in a downstream reducing flame zone. The present work is intended to raise the devolatization rate to promote the initial $NO_x$ reduction for