Reduction of NO_x Emission from Gas Burner System Via Staged Combustion/Reburning

M. N. Mohd-Jaafar
Mechanical Engineering Faculty,
Universiti Teknologi Malaysia,
Karung Berkunci 791, 80990 Johor Bahru, Johor
Malaysia

G.E. Andrews and **M.C. MkPadi**
Department of Fuel and Energy
University of Leeds
Leeds LS2 9JT
United Kingdom

Abstract: NO_x reduction of more than 50 percent were achieved at 30 per cent excess air with corrected NO_x emission of less than 10 ppm at this condition for a burner system using radial swirler with lean/lean fuel staged combustion. Very low NO_x and CO emissions were also achieved at very low excess air with equivalence ratios of 0.85-0.9. Further reduction was achieved by reducing the pressure losses by means of reducing the airflow rates into the system. The lowest pressure loss having the highest reduction of almost 80 per cent at equivalence ratio of near 0.875.

Keywords: *Staged combustion, NO_x*

INTRODUCTION

The need to protect the environment from combustion generated NO_x has led to considerable demand to improve burner design. Previously, attention has been given to gas turbine used in aero engines and for power generation in stationary plant. Intense research has been going on to develop gas turbine with very low NO_x emissions. In recent years considerable attention has been paid to reducing NO_x from process burners. However, in order to minimize NO_x emissions from gas turbine combustor it is necessary to increase the primary zone airflow and to improve air and fuel mixing. Many low-emission gas turbine combustor designs aim to pass as much air as possible through the combustor head and add the remaining air further downstream in a dilution zone with no air needed for film cooling [1]. The primary zone is a burner configuration [1]. Thus, many of the methods used to effectively minimize NO_x emissions from gas turbine can be adapted to burner configurations and conditions. This work is based on the low NO_x radial swirler work of Al-Kabie [2], Escott [3] and Kim [4] applied to burner applications of the 5-45kW thermal input.

The effects of increased levels of NO_x in the atmosphere are wide reaching. In the atmosphere NO is rapidly oxidised to NO_2 and in this form plays an essential role in the formation of tropospheric ozone and photochemical smog, and is oxidised to form nitric acid that may then be deposited as acid rain [5]. At ground level, increased concentrations (above 0.06 ppm) of NO_2 can cause respiratory problem [6].

The legislation of NO_x emission limits in many parts of the world has substantially complicated the process of burner design. Attempts at lowering NO_x emissions by reducing the flame temperature will lead to reduced flame stability or increased CO emissions. The lowest NO_x emission obtainable in a given configuration is always limited by unacceptable stability problems or CO emissions. Thus the burner design has become a trial-and-error, multi-parameter optimisation process [7].

Basically there are two techniques of controlling NO_x: those which prevent the formation of nitric oxide (NO) and those which destroy NO from the products of combustion. In the present work both methods are employed: lean combustion for low thermal NO_x followed by second stage fuel injection for combustion in the combustion products of the lean zone, which can destroy first stage NO_x through a reburn mechanism.

The methods that prevent the formation of NO involved modifications to the conventional burner designs or operating conditions, such as lean primary zone, rich primary zone, rich/lean, or reduced residence time, since the main factors governing formation of NO is temperature and oxygen availability. However, the rich/lean method tends to increase CO and UHC. Advanced combustor designs are needed for reducing all four major pollutants simultaneously over a range of thermal or engine power outputs. This gives rise to the use of variable geometry combustor and staged combustion to cope with the demands of burner turndown and power variations in gas turbines, when the overall A/F is increased as power is reduced. For ultra low NO_x emissions, lean premixed-prevaporised combustors and catalytic combustors are being developed.

In staged combustion, the combustion process is arranged to occur in a number of discrete stages. In theory, circumferential, radial or axial staging may be employed. However, in practice circumferential fuel staging increases NO_x - instead of the fuel being distributed uniformly around the liner, it is injected at a small number of points, where it produces regions of high temperature [8]. The elaboration's for the above mentioned three types of fuel staging are as follows:

a) *Circumferential.* Usually this entails disconnecting alternately located nozzles from the fuel supply. It is ideally suited to tuboannular systems but on annular chambers its advantages are largely offset by the quenching effects of the surrounding cold air on the localised burning zones.
b) *Radial.* The simplest application of this technique is to double-banked annular combustors where, at low fuel flows, it is a relatively simple matter to inject all the fuel into the inner or outer combustion zone.
c) *Axial.* By designing the primary zone for optimum performance at low power settings, and then injecting the extra fuel needed at higher power levels at one or more locations downstream.

In the present work axial fuel staging was employed that consisted of lean-lean combustion. The first combustor was operated very lean with all the air needed for combustion introduced in this zone and the operation was set close to the lean stability limit. Fuel, without any air, was then injected into the completely burnt products of this lean primary combustion zone to bring the burner to the desired overall excess air. Typically the lean zone may have an equivalence ratio of 0.6 with fuel injected in the secondary zone to bring the overall equivalence ratio to 0.9. Thus, it is a lean/lean staged system. However, the inert second stage fuel injection will create a local rich zone near the injector prior to mixing with oxygen from the lean primary zone exhaust. Thus, the burner will have element of lean/rich/lean combustion, which is a key feature of NO_x reduction using staged combustion.

STAGED COMBUSTION/REBURNING

Reburning, or sometimes referred to as in-furnace NO_x reduction, was first proposed by Wendt et al. in 1973 [9]. However, much earlier studies had shown that NO could be reduced by reaction with hydrocarbon fragments ([10], [11]). This method of reducing NO_x emissions only became successful when Takahashi et al. [12] showed that a NO_x reduction of at least 50% could be achieved by applying this method. Reburning or fuel staging is primarily the introduction of secondary fuel downstream of the primary zone any associated airflow. In this method the formation of the NO_x is allowed to be completed in the primary zone. Then the reburn fuel is injected further downstream, where it is expected that the formation of NO_x from the primary zone is completed. This reburn fuel, usually hydrocarbon fuel, is injected to destroy the NO_x that was formed in the primary zone. The reaction of this destruction is given as follows:

$CH + NO \rightarrow HCN + O$ (1)

HCN participates in a series of reactions leading to the formation of a partially equilibrated pool of NH_i species. The amine radicals either react with NO to produce N_2 or are oxidised to reform NO.

The reburn process is composed of three distinct zones. The first zone is the *primary combustion zone.* In this zone the fuel is burnt lean. For furnace application, usually 80% of the total fuel is introduced in this zone. The formation of NO_x is usually completed in this zone. The next zone is the *reburn zone* or sometimes called the reduction zone since in this zone the NO_x formed in the primary zone is reduced to molecular nitrogen. In this zone the fuel is burnt at rich condition. The reburn fuel is injected downstream of the primary zone. The final zone is called the *burnout zone.* In this zone the additional air is added to create an overall lean condition and to oxidise the remaining unburnt fuel fragments and CO, thus, completing the combustion process. The reburn combustion system is thus lean/rich/lean staged combustion.

There are several parameters that control the effectiveness of the reburning process. These are listed as follows:

1. The initial concentration of NO_x from primary zone ([13]; [14] and [15]).
2. The equivalence ratio of the reburn zone ([13], [15] and [16]).
3. The residence time in the reburn zone [15].
4. The completeness of the primary zone combustion prior to the injection of the reburn fuel [15].

There are other fuels that can be used as the reburn fuel instead of hydrocarbon fuels. However, many workers in this area agreed that natural gas is the best reburn fuel to be used. The hydrocarbon fuel rapidly forms CH fragments that convert the primary zone NO to HCN via the reaction (1). They also agreed that in order to destroy NO formed in the primary zone effectively the stoichiometric ratio of about 0.9 (i.e., 10% rich) is the optimum value for the reduction zone. The stoichiometric ratio is defined as the inverse of equivalence ratio.

In the present work, the staged combustion process was applied to burner a lean/lean system. However, in this configuration there are only two distinct zones involved. The burnout zone was eliminated due to rig complexity. Natural gas was used as the reburn fuel. The initial zone was set at about 0.6 equivalence ratio with the total burner airflow in the initial zone. Secondary fuel was injected into the combustion products, which had ample oxygen. The secondary fuel was varied to vary the overall equivalence ratio from 0.6 to 1.0 and compared with putting all the fuel in the initial zone.

EXPERIMENTAL SET-UP

The general set-up for a staged combustion system comprised of two different sizes flame tubes. The smaller one of 76mm inside diameter was attached to the plenum chamber and acted as the first stage. The radial swirler of 40mm outlet diameter and 21.5mm depth was used as a flame stabiliser. The first combustor was fuelled via the radial vane passage injection mode. The air and fuel were mixed thoroughly prior to ignition. At the exit plane of the first combustor a wall fuel injector of 76mm diameter was attached. This is the injector for the second stage reburn fuel. The mixtures of flue gas from the first combustor and the reburn fuel were allowed to expand freely into a larger combustor of 140mm internal diameter. The wall injector and the second combustor were attached to the first combustor by the used of flanges. The schematic diagram of set-up of reburn test rig is shown in Diagram 1.

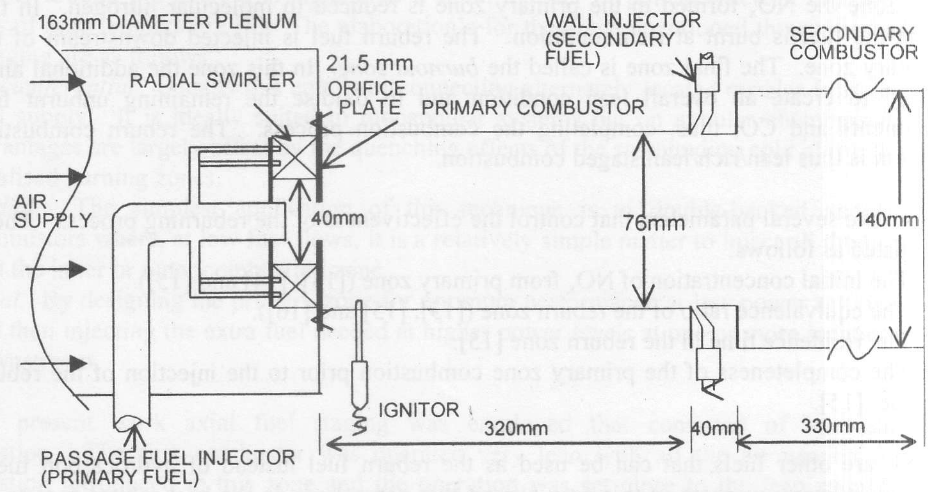

Diagram 1: *Schematic of Staged Combustion Set-up.*

The staged combustion tests were run at several different pressure losses to achieve burner modulation, different thermal output at the same excess air. The radial swirler in the primary zone in Diagram 1 has a swirler outlet of 40mm. This could be fitted with different orifice plates to reduce the swirler outlet areas. The role of the orifice plate was to enhanced flame stabilisation and provide a better mixing of the air and fuel prior to ignition. It also created the pressure loss at the outlet rather than in the vane passage which generated maximum turbulence in the swirl shear layer. The orifice plate also helped to prevent fuel from entraining into the corner dumped expansion outer recirculation zone and thus create a rich local zone which would lead to higher NO_x emissions from this area. The orifice plate was mounted at the exit plane of the radial swirler as shown in Diagram 1.

All the tests were carried out at atmospheric pressure with an air inlet temperature of 400K, with burner upstream pressures of 40, 30, 20 and 10mmH_2O. These cover a range of practical domestic central heating burner conditions.

RESULTS AND DISCUSSIONS

Figures 1-4 show the staged combustion test results as compared to the baseline results with all the fuel supplied to the primary swirler with varying pressure losses. As can be seen generally, a marked reduction of almost 80% in corrected NO_x to 0% oxygen on a dry basis was achieved for a pressure loss of 10mmH_2O at an equivalence ratio of 0.875 as shown in Figure 4(b).

Figure 1(b) shows that a NO_x reduction of 36ppm (69.2%) was obtained at an equivalence ratio of 0.89. However, the rich condition was limited by a drastic increase in carbon monoxide (CO) emission to an unacceptable value. The combustion inefficiencies of less than 0.01% were obtained between 0.67 and 0.84 equivalence ratios. This shows that a combustion efficiency of 99.99% was achievable for a wide range of equivalence ratios.

CO emissions of lower than 10ppm were obtainable over a wide range of equivalence ratios up to 0.8. However, these values are higher than the baseline values (see Figure 1(d)). This CO increases was due to the lower residence time with staged combustion and the lower oxygen availability. Unburned hydrocarbon (UHC) emissions of less than 6ppm were achieved over the entire operating range of equivalence ratios (Figure 1(c)).

Figures 2-4 show the same trend of results for lower burner pressure losses of 30, 20 and 10mm H_2O. A reduction of 53ppm (79%) was obtained at an equivalence ratio of 0.885 (see Figure 2(b)) for the pressure loss of 30mmH_2O. This is at 14ppm reburn NO_x. Combustion inefficiencies of 0.004% were obtained over the range of equivalence ratios from 0.647-0.79 (Figure 2(a)). Figure 2(d) shows CO emissions of less than 10ppm were obtained over the entire range of equivalence ratios up to about 0.8 before rising sharply. UHC emissions were 1ppm over the entire range of equivalence ratios (Figure 2(c)).

At 20mmH_2O pressure loss, a reduction of 31ppm (65.96%) in NO_x was obtained at an equivalence ratio of 0.89 (Figure 3(b)). Figure 3(a) shows a relatively narrow margin of operating equivalence ratios (between 0.72 and 0.82) where combustion inefficiencies were

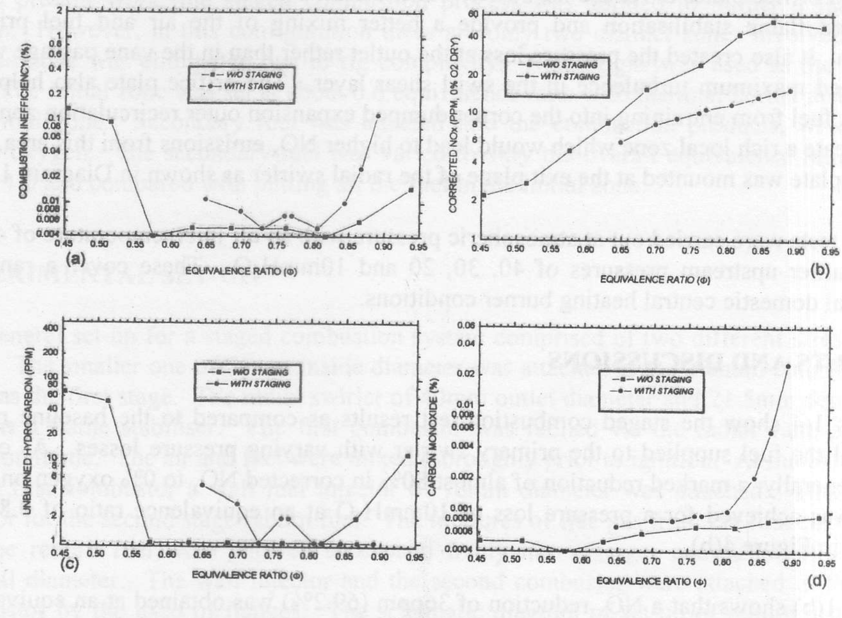

Figure 1: Exhaust emissions vs. equivalence ratio for 25 mm orifice plate @ $\Delta P = 40$ mmH_2O; $T_{in} = 400^o$ K

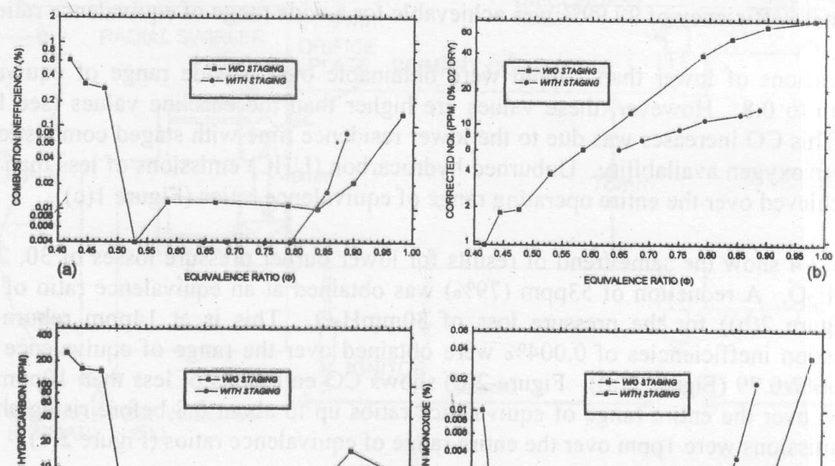

Figure 2: Exhaust emissions vs. equivalence ratio for 25 mm orifice plate @ $\Delta P = 30$ mmH_2O; $T_{in} = 400^o$ K

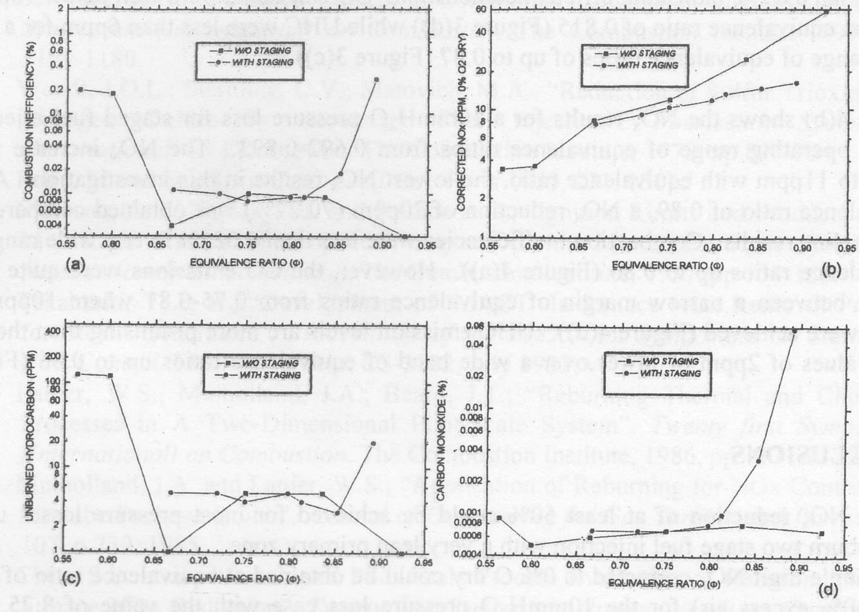

Figure 3: Exhaust emissions vs. equivalence ratio for 25 mm orifice plate @ $\Delta P = 20\ mmH_2O$; $T_{in} = 400^o$ K

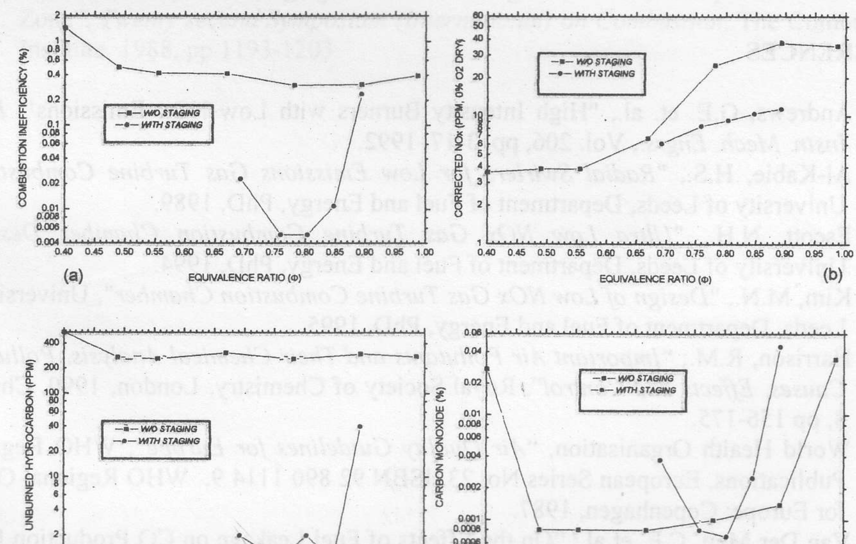

Figure 4: Exhaust emissions vs. equivalence ratio for 25 mm orifice plate @ $\Delta P = 10\ mmH_2O$; $T_{in} = 400^o$ K

lower than 0.01%, indicating efficient combustion. CO emissions were well below 10ppm up to an equivalence ratio of 0.815 (Figure 3(d)) while UHC were less than 6ppm for a wide range of equivalence ratios of up to 0.87 (Figure 3(c)).

Figure 4(b) shows the NO_x results for a 10mmH_2O pressure loss for staged fuel injection for an operating range of equivalence ratios from 0.692-0.893. The NO_x increase from 6ppm to 11ppm with equivalence ratio, the lowest NO_x results in this investigation. At an equivalence ratio of 0.89, a NO_x reduction of 20ppm (70.27%) was obtained compared to the baseline results. Combustion inefficiencies were less than 0.025% over a wide range of equivalence ratios up to 0.86 (Figure 4(a)). However, the CO emissions were quite high except between a narrow margin of equivalence ratios from 0.75-0.81 where 10ppm or lower were achieved (Figure 4(d)). UHC emission levels are more promising than the CO with values of 2ppm or lower over a wide band of equivalence ratios up to 0.86 (Figure 4(c)).

CONCLUSIONS

1. A NO_x reduction of at least 50% could be achieved for most pressure losses using reburn two stage fuel injection with a very lean primary zone.
2. Single digit NO_x corrected to 0% O dry could be obtained at equivalence ratio of 0.78 (30% excess air) for the 10mmH_2O pressure loss case with the value of 8.75 ppm obtained at this equivalence ratio.

REFERENCES

[1] Andrews, G.E. et. al., "High Intensity Burners with Low NOx Emissions", *Proc. Instn. Mech. Engrs.*, Vol. 206, pp. 3-17. 1992.

[2] Al-Kabie, H.S., "*Radial Swirlers for Low Emissions Gas Turbine Combustion*", University of Leeds, Department of Fuel and Energy, PhD, 1989.

[3] Escott, N.H., "*Ultra Low NOx Gas Turbine Combustion Chamber Design*", University of Leeds, Department of Fuel and Energy, PhD, 1994.

[4] Kim, M.N., "*Design of Low NOx Gas Turbine Combustion Chamber*", University of Leeds, Department of Fuel and Energy, PhD, 1995.

[5]. Harrison, R.M.; "*Important Air Pollutants and Their Chemical Analysis. Pollution: Causes, Effects and Control*", Royal Society of Chemistry, London, 1990, Chapter 8, pp 156-175.

[6] World Health Organisation, "*Air Quality Guidelines for Europe*", WHO Regional Publications, European Series No. 23, ISBN 92 890 1114 9. WHO Regional Office for Europe: Copenhagen, 1987.

[7] Van Der Meij, C.E. et al.; "On the Effects of Fuel Leakage on CO Production From Household Burners as Revealed by LIF and CARS", *Twenty fifth Symposium (International) on Combustion*, The Combustion Institute, 1994, pp 243-250.

[8] Lefebvre, A.H.; "Pollution Control in Continuous Combustion Engines", *Fifteenth Symposium (International) on Combustion*, The Combustion Institute, 1975, pp 1169-1180.

[9] Wendt, J.O.L.; Sternling, C.V.; Matovich, M.A.; "Reduction of Sulfur Trioxide and Nitrogen Oxides by Secondary Fuel Injection", *Fourteenth Symposium (International) on Combustion*, The Combustion Institute, 1973, pp 897-904.

[10] Patry, M and Engel, G; *C. R. Acad. Sci. Paris* 1950, **231**, 1302.

[11] Myerson, A.L., Taylor, F.R. and Faunce B.G.; "Ignition Limits and Products of the Multistage Flames of Propane-Nitrogen Dioxide Mixtures", *Sixth Symposium (International) on Combustion*, The Combustion Institute, 1957, pp 154-163.

[12] Takahashi, Y. et al., "Development of 'MACT' In-furnace NOx Removal Process for Steam Generators", *Proceedings of the 1982 Joint Symposium on Stationary NOx Control*, EPRI Report No. CS-3182, July 1983, vol. 1.

[13] Lanier, W.S.; Mulholland, J.A.; Beard, J.T.; "Reburning Thermal and Chemical Processes in A Two-Dimensional Pilot-Scale System", *Twenty first Symposium (International) on Combustion*, The Combustion Institute, 1986, pp 1171-1179.

[14] Mulholland, J.A. and Lanier, W.S.; "Application of Reburning for NOx Control to a Firetube Package Boiler", *Journal of Engineering for Gas Turbine and Power*, vol. 107, p 739, 1985.

[15] Chen, S.L. et al., "Bench and Pilot Scale Process Evaluation of Reburning for In-furnace NOx Reduction", *Twenty first Symposium (International) on Combustion*, The Combustion Institute, 1986, pp 1159-1169.

[16] Kolb, T., Jansohn, P. and Leuckel, W.; "Reduction of NOx Emission in Turbulent Combustion by Fuel-Staging/Effect of Mixing and Stoichiometry in the Reduction Zone", *Twenty second Symposium (International) on Combustion*, The Combustion Institute, 1988, pp 1193-1203.