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Reduction of NO_x Emission from Gas TURBINE COMBUSTOR Applying Fuel-Staged Combustion

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A two-stage lean/lean gas turbine combustor was developed with low NO_x characteristics in each stage using a small radial swirler of 40-mm outlet diameter in the pilot stage. Both flame tubes were arranged in series with the smaller combustor (76 mm inside diameter) as the pilot stage and the larger combustor (140 mm inside diameter) as the main stage. The pilot stage was fuelled via vane passage fuel injector, while the main stage was fuelled around the wall of the exit plane of the pilot stage, using wall fuel injectors.

Low NO_x emissions were obtained when using fuel staging for methane fuel, as low as 6 ppm. A NO_x reduction of more than 40 % was obtained at equivalence ratio of near 0.7, when using fuel staging compared to the non-fuel-staging test. Tests were conducted using methane as fuel. This was achieved at very small increase in carbon monoxide emissions especially near the rich region and with almost no increase at all in the unburned hydrocarbon emissions at the same equivalence ratio.

Keywords: NOx emissions, fuel staging, carbon monoxide, swirler.

INTRODUCTION

The effects of increased levels of NO_x in the atmosphere are wide reaching. In the atmosphere, NO is rapidly oxidized to NO_2 and in this form, plays an essential role in the formation of tropospheric ozone and photochemical smog. It is oxidized to form nitric acid that may then be deposited as acid rain [1]. At ground level, increased concentrations (above 0.06 ppm) of NO_2 can cause respiratory problems [2].

The legislation of NO_x emission limits in many parts of the world has substantially complicated the process of combustor design. Attempts at lowering NO_x emissions by reducing the flame temperature will lead to reduced flame stability or increased CO emissions. Unacceptable stability problems or CO emissions always limit the lowest NOx emission obtainable in a given configuration. Thus, the combustor design has become a trial-and-error, multi-parameter optimization process [3].

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 combustor 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. Water or steam injection has been shown to be a very effective technique to reduce flame temperature [4]. However, to avoid detrimental effects on turbine durability, the water has to be purified to a maximum of 2-5 ppm of dissolved solids [5], [6]. Furthermore, there are other complications, such as incorporating the water injection system to the combustor design. Another disadvantage of water injection is the undesirable side effects of quenching CO burnout. These drawbacks caused the water injection method to be unattractive for smaller gas turbines or where availability of sizeable water supply is difficult. However, it is a feasible technique for burner NO_x control in water heater or steam generator.

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 power variations in gas turbines, when the overall A/F is increased as power is reduced. For ultra low NO_x emissions, lean premixed-prevaporized 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, either 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 [7]. An elaboration 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 the quenching effects of the surrounding cold air on the localized burning zones largely offset its advantages.
b) *Radial.* The simplest application of this technique is to double-bank annular combustors where, at low fuel flows, 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 combustor to the desired overall excess air.

EXPERIMENTAL SET-UP

This system comprised of two different sizes of flame tubes. The smaller one with an inside diameter of 76 mm was attached to the plenum chamber and acted as the first stage. The radial swirler of 40 mm outlet diameter and 30.5 mm depth was used as a flame stabilizer. 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 76 mm 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 140 mm 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.

The reburn tests were run at 2.4% pressure losses to achieve lowest gas turbine combustor condition. The radial swirler in the primary zone in Diagram 1 has a swirler outlet of 40 mm. All the tests were carried out at atmospheric pressure with an air inlet temperature of 600 K, gas turbine pressure loss of 2.4%, and fuelled using methane. In all the tests, methane, used as fuel, contains 92.45% CH_4, 5.34% C_2H_6, 1.24% N_2, 0.45% CO_2, 0.4% C_3H_8 and 0.12% O_2 by mole fraction. The fuel was pressurized using a compressor to allow for sufficiently adequate fuel mass flow rates. The fuel flow rate was metered by three

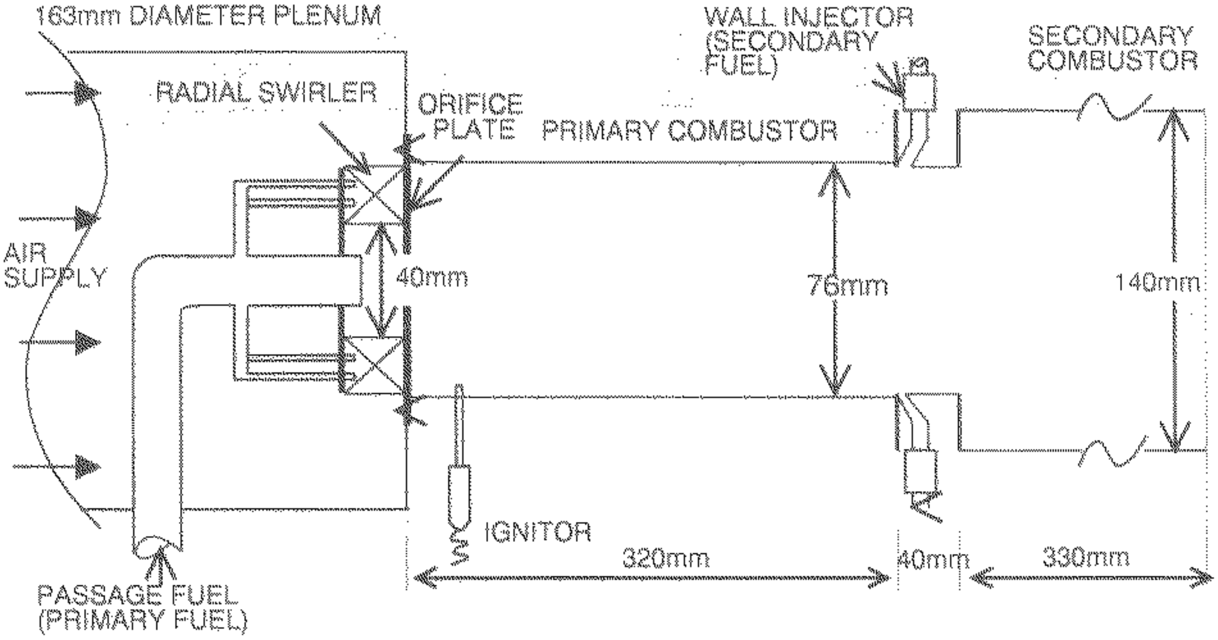

Diagram 1 Schematic Diagram of Reburn Test Set-up Rig

GEC-Marconi series 2000 rotameters with a combined range of 0-680 liters/min. The reburn fuel was metered using a smaller range rotameter of 2.5-22 liters/min manufactured by KDG MOBREY Series 2000.

There were two systems of supplying air for different air requirements: one of which used an air blower and the other used the laboratory compressed air supply. The higher volume requirements of air, usually needed for gas turbine conditions, used the fan blower; whereas the lower volume requirements of air, usually needed for domestic central heating burner systems, used the compressed air supply from the laboratory. In the present work, the former air supply system was adopted.

The compressed air was passed through a variable area flow meter. A pressure tapping was used to monitor the inlet static pressure to the rotameter. The inlet temperature was monitored by a chrome-alumel type-K thermocouple fixed between the rotameter and the control valve. The air flow rates were then calculated, corrected for inlet temperature and pressure deviation from the rotameter calibration values of 15°C and 760mm mercury barometric pressure.

The metered air was heated to the desired air inlet temperature using three electrical heaters of 3 kW each that were arranged in series totalling up to 9kW of heat. In this case, the preheat temperature is 600 K. The heater elements were connected to the air supply plenum chamber by a 90° connector. The heater and the plenum chamber connected to the combustor were thermally insulated with 25mm thick kaowool in order to prevent heat losses. The insulated sections also were covered with a reflecting foil backed gauze material. The pre-heated air was then admitted into the combustor via the plenum chamber and the radial swirler. The function of the plenum chamber was to provide a uniform air distribution prior to entering the radial swirler. The preheated air temperature was measured using a chrome-alumel type-K thermocouple positioned on the central axis and 100mm upstream of the combustor inlet plane. The inlet static pressure of the combustor was measured using four static pressure tappings with the same manifold positioned 150mm upstream of the combustor inlet plane.

The exhaust gas was sampled continuously by the gas analyzers. These analyzers were capable of a complete on-the-spot analysis of CO_2, UHC, CO, NO, NO_x and O_2. The sampling system was designed and constructed to ensure that a representative samples were delivered to the various instruments.

An 'X' configuration gas sampling probe with 40 holes on centre of equal areas was used for mean exit sampling. It consisted of two stainless steel tubes welded eccentrically with water circulating in between the tubes to cool the

Table 1 Gas Analysis Instrumentation.

Gas Component	Method of Analysis	Reading Ranges	Manufacturer
CO_2	Non-dispersive Infra-Red	4 ranges 0 - 0.1% 0 - 15%	A.D.C.
CO	Non-Dispersive Infra-Red	4 ranges 0 - 100ppm 0 - 1000ppm 0 - 1% 0 - 10%	A.D.C.
UHC	Flame Ion Detection	7 ranges 0 - 100ppm 0 - 10%	Signal Instrument
NO/NO_x	Chemiluminescent (Carbon Converter)	7 ranges 0 - 4ppm 0 - 400ppm	B.O.C. Luminox
O_2	Paramagnetic	0 - 100%	Taylor Instrument Servomex

exhaust gases and the probes. The sample was transported to the gas analyzers along a 7.6m heated Teflon sample line to be analysed for CO_2, UHC, CO, NO, NO_x and O_2.

The sample gas from the combustor was pumped into the oven to draw samples to the analysers. The sample gas was filtered in the oven and kept at 150°. The sample gas was then fed to the analysers to be measured. The gas instrument used and their detection ranges are summarised in Table 1.

The gas was analyzed for CO and CO_2 using an Analysis Development Co. non-dispersive infra red, NDIR, analysers. The CO and CO_2 infra red analysers had two cells and two electrical amplification ranges. The CO analyzer had four ranges between 0-100 ppm and 0-10%, the CO_2 analyzer also had four ranges but these were between 0-0.1% and 0-15%.

Flame ionization detectors (FID) were used to measure hydrocarbon (UHC) concentration in the sample gas. Fuel for the flame in the FID was a cocktail of 60 percent hydrogen and 40 percent helium burning in zero grade air which was used to reduce the sensivity of the FID responses to the sample oxygen level. In FID, analyzers prouded the electrical resistance of a H_2-He flame is monitored and when a sample gas that contains compound with C-H bonds is introduced to the flame ionization occurs with a subsequent reduction in the resistance of the flame. The resistance reduction is directly proportional to the concentration of UHC molecules present in the sample gas that is introduced to the flame. To prevent condensation of heavier hydrocarbon in the sample gas the sample gas lines to the FID analyser are kept heated at 150°C.

The oxygen concentration in the sample gas was measured by a Servomex paramagnetic analyser with a single range of 0-100%. It was powered by self-contained batteries. Oxygen has the property of being paramagnetic due to the molecules unpaired electrons. The analyzer measures the paramagnetic susceptibility of the sample gas with oxygen content by means of a proven magneto-dynamic type measuring cell.

The NO_x emissions in the sample gas were measured using a B.O.C. chemiluminescent analyzer (Luminox). The analysis of NO_x in the sample gas is based on the emission of light radiation resulting from the reaction between NO and O_3. The intensity of the light emitted is measured by a photon detector and is proportional to NO concentration. A carbon-molybdenum

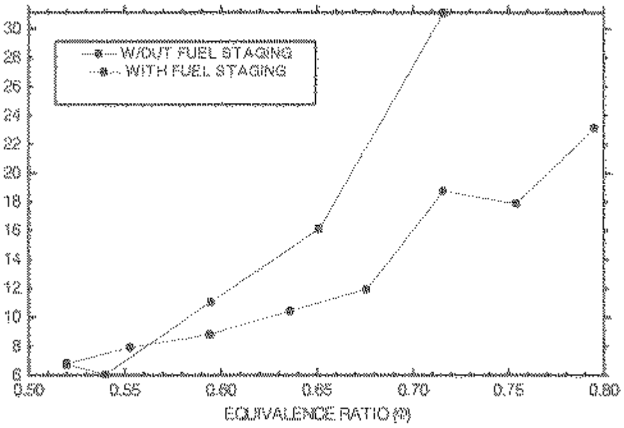

Figure 1. Corrected NOx Emission vs. Equivalence Ratio for ΔP/P=2.4%

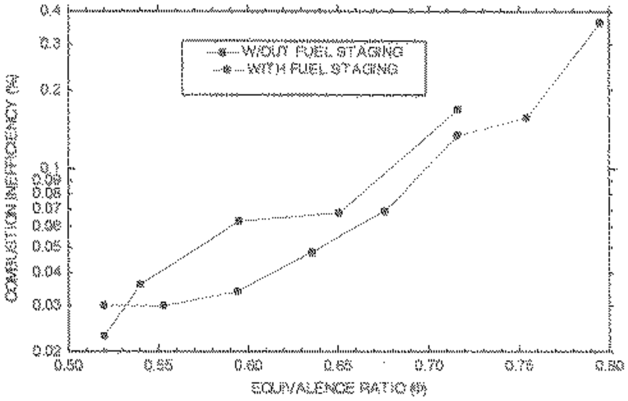

Figure 2. Combustion Inefficiency vs. Equivalence Ratio for ΔP/P=2.4

converter was used to convert NO_2 from the sample gas to NO ahead of the reaction chamber and its temperature was controlled at 400°C. The ozone was generated from zero grade air from the air purification system (APS). The air purifier was manufactured by Signal Instruments Control.

Prior to any data being taken, all the analysers had to be calibrated. The analysers were calibrated using high accuracy calibration gases. A typical composition of the calibration gas manufactured by Bedfont Scientific Ltd.

The raw data recorded was then fed to a huge computer programme to calculate the parameters required such as fuel mass flow, gas analysis based equivalence ratios, air humidity, adiabatic flame temperature, combustion inefficiency, and corrected NO_x emissions.

Results and Discussion

Figures 1-4 show the plots of corrected NO_x emission to 15 % oxygen, combustion inefficiency, carbon monoxide and unburned hydrocarbon emissions plotted against operating equivalence ratios.

The general trend can be seen that by applying fuel staging or reburning, NO_x emissions are lower. This can be seen clearly in Figure 1, for the entire range of operating equivalence ratios. However, on the leaner side, i.e. at lower equivalence ratios, NO_x emissions due to reburning seem to be higher than that when not applying fuel staging. There is no logical explanation for this phenomenon, but an error during recording the emissions data may have caused this problem.

A corrected NO_x emission of lower than 20 ppm was achieved at equivalence ratio of 0.7 when using fuel staging. Ultra-low NO_x of 6 ppm was also achieved at the leanest condition. NO_x reduction of 43.8 % was obtained at equivalence ratio of 0.7, when using fuel staging compared to the non-fuel staging tests.

From Figure 2, again, the general trend was apparent when applying fuel staging. It can be seen that when applying fuel staging, the combustion efficiencies were higher than when not applying fuel staging over the entire range of operating equivalence ratios. Combustion efficiencies of greater than 99.9 % were achieved up to near 0.7 equivalence ratios implying the very good mixing of the fuel and air prior to ignition was achieved. This can be attributed to the insertion of orifice plate at the exit plane of the radial swirler.

Even for carbon monoxide (CO) emissions, the fuel staging results show lower values than when not applying fuel staging (Figure 3). This is a very good indication since normally, any techniques to reduce NO_x emissions will tend to increase CO. However, in the present work, it is found that even CO emissions were reduced when applying fuel staging.

Figure 3 shows CO emissions of less than 100 ppm and was obtained over a wide range of equivalence ratios up to 0.67. This is very close to the condition without fuel staging. However, fuel staging increases the CO emissions higher than 100 ppm for equivalence ratio of above 0.67 due to the lower residence time with reburn and the lower oxygen availability.

Unburned hydrocarbon (UHC) emissions were also lower when applying fuel staging compared to that when not using fuel staging. This was achieved over a wide range of operating

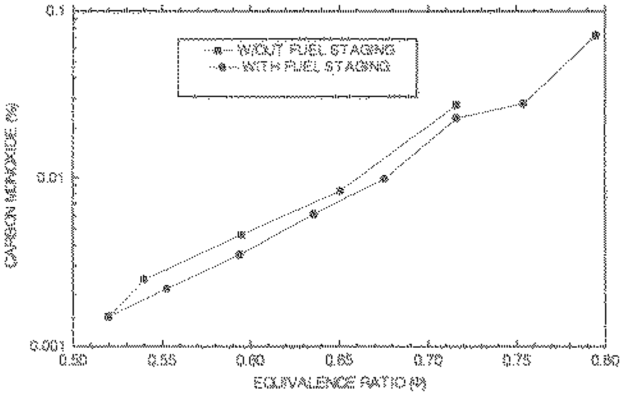

Figure 3. Carbon Monoxide vs. Equivalence Ratio for $\Delta P/P=2.4\%$

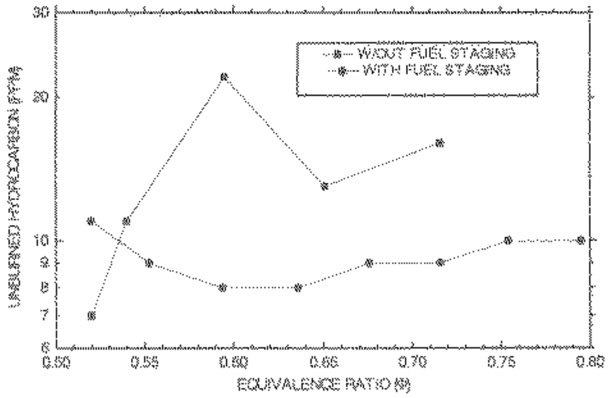

Figure 4. Unburned Hydrocarbon vs. Equivalence Ratio for $\Delta P/P=2.4$

equivalence ratios. UHC of less than 10 ppm was achieved for the entire range of operating equivalence ratios when applying fuel staging. This is apparent in Figure 4.

CONCLUSIONS

A NO_x reduction of more than 40% could be achieved when applying fuel-staged combustion with a very lean primary zone. Very good combustion efficiencies were also obtained with significant decrease, in CO and UHC emissions.

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