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Application of Fuel Staging on Reducing No_x from Domestic Central Heating Burner System

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Abstract

NO_X reduction of more than 50 per cent were achieved at 30 per cent excess air with corrected NO_x emission of less than 10 ppm at this condition for a domestic central heating burner system using radial swirler with lean/lean fuel staged combustion. This value is much lower than the conventional laminar bar burner used for domestic central heating. 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 82 per cent at equivalence ratio of near 0.85.

Introduction

The effects of increased levels of NO_x in the atmosphere are wide-reaching. In the atmosphere NO is rapidly oxidised to NO_2 which 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 [1]. At ground level, increased concentrations (above 0.06 ppm) of NO_2 can cause respiratory problem [2]. 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 [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 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 are temperature and oxygen availability. However, the rich/lean method tends to increase CO and unburned hydrocarbon (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, 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 [4]. The elaboration's for the above mentioned three types of fuel staging are as follows:

- *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.
- *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 (See Fig. 1).

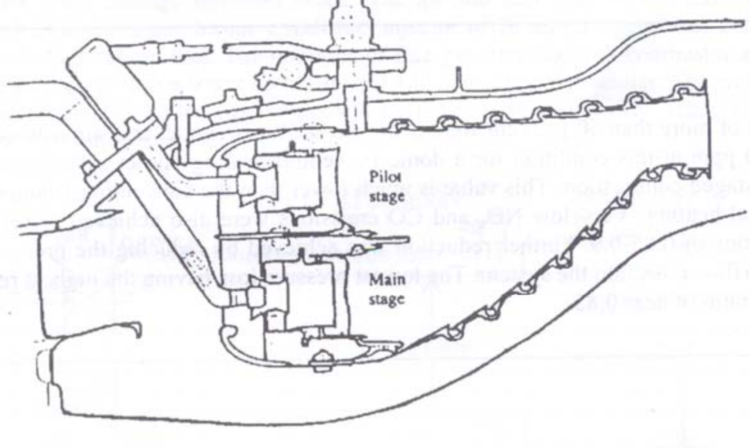

Fig.1. Radial staging configuration.

- *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. (See Fig. 2).

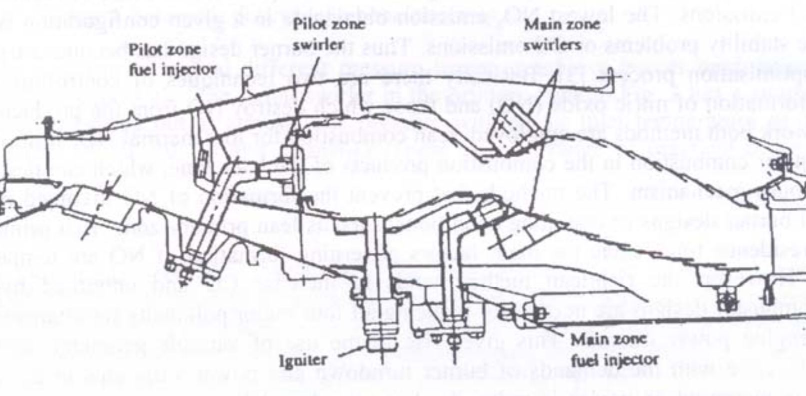

Fig. 2. Axial or tandem staging configuration

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 reburning.

Fuel staging/reburning

Reburning, or sometimes referred to as in-furnace NO_x reduction, was first proposed by Wendt et al. in 1973 [5]. However, much earlier studies had shown that NO could be reduced by reaction with hydrocarbon fragments [6] & [7]. This method of reducing NO_x emissions only became successful when Takahashi et al. [8] showed that a NO_x reduction of at least 50 per cent could be achieved by applying this method. Reburning or fuel staging is primarily the introduction of secondary fuel downstream of the primary zone without 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 hydrocarbons fuel, is injected to destroy the NO_x that was formed in the primary zone. The reaction of this destruction is given as follows:

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

The 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 that is 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:

- The initial concentration of NO_x from primary zone [9], [10], & [11].
- The equivalence ratio of the reburn zone [9], [11], & [12].
- The residence time in the reburn zone [11].
- The completeness of the primary zone combustion prior to the injection of the reburn fuel [11].

There are several other parameters that affect the reburn process such as the temperature of the reburn zone, dispersion of reburn fuel and concentration of oxygen from the primary zone [11]. Despite all these parameters, a reduction of 50 per cent in NO_x emissions was achieved. 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 reburning 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 since the existing rig was not able to supply secondary air due to the assembly of the flame tubes. 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. This constitutes of about 60-70% of total fuel supplied to the system. 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, i.e. from about 0-30 or 40% of the total fuel supplied to the system and compared with putting all the fuel in the initial zone.

Experimental set up

The general rig set-up for a fuel staged combustion system comprised of two different sizes flame tubes. The smaller one of 76 mm inside diameter was attached to the plenum chamber and acted as the first stage. The radial swirler of 40 mm outlet diameter and 215 mm 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 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 use of flanges. The schematic diagram of set-up of fuel staging test rig is shown in Fig. 3.

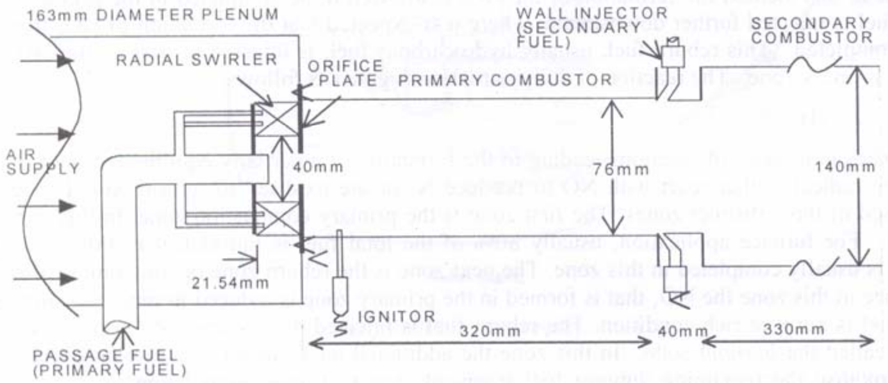

Fig. 3. Schematic diagram of reburn test set-up rig.

The fuel staging 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 Fig. 3 has a swirler outlet of 40mm. All the tests were carried out at atmospheric pressure with an air inlet temperature of 400K, with burner upstream pressures of 40, 20, 10 and 5mmH_2O. These cover a range of practical domestic central heating burner conditions.

Results and discussions

Fig. 4-7 show the fuel staging test results as compared to the baseline results with all the fuel supplied to the primary zone (100% of total fuel to the system) with varying pressure losses to achieve burner modulation at the same excess air. As can be seen generally, a marked reduction in NO_x emissions can be achieved. The largest reduction of 82 per cent in corrected NO_x to 0 percent oxygen on a dry basis was achieved for a pressure loss of 5 mm H_2O at an equivalence ratio of 0.84 as shown in Fig. 7d.

Fig. 4b shows CO emissions of less than 10 ppm were obtained over a wide range of equivalence ratios up to 0.745. Even at an equivalence ratio of 0.8 the CO emission was only 15 ppm. The lowest CO emission was 6 ppm at an equivalence ratio of 0.65. However, fuel staging increases the CO to 100 ppm for an equivalence ratio of 0.9 but were acceptable at 15 ppm for an equivalence ratio of 0.78. This CO increases was due to the lower residence time with fuel staging and the lower oxygen availability. Unburned hydrocarbon (UHC) emissions of less than 5 ppm were achieved for the entire range of operating equivalence ratios.

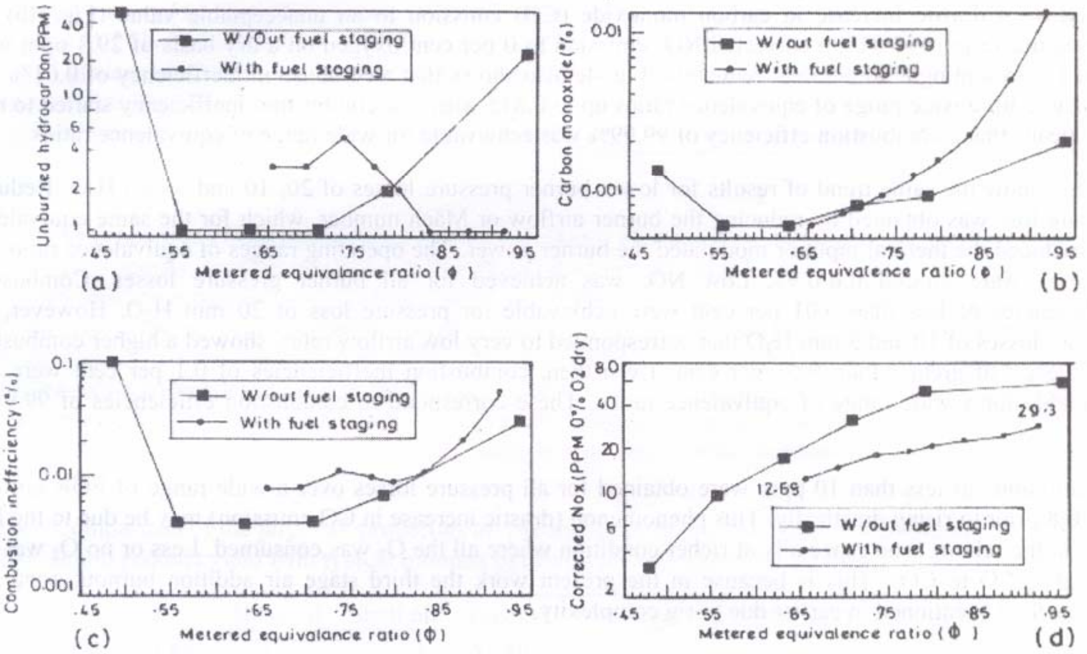

Fig. 4. Mean emissions vs. equivalence ratio for no orifice plate @ ΔP = 40 mm H_2O; T_m = 400 K

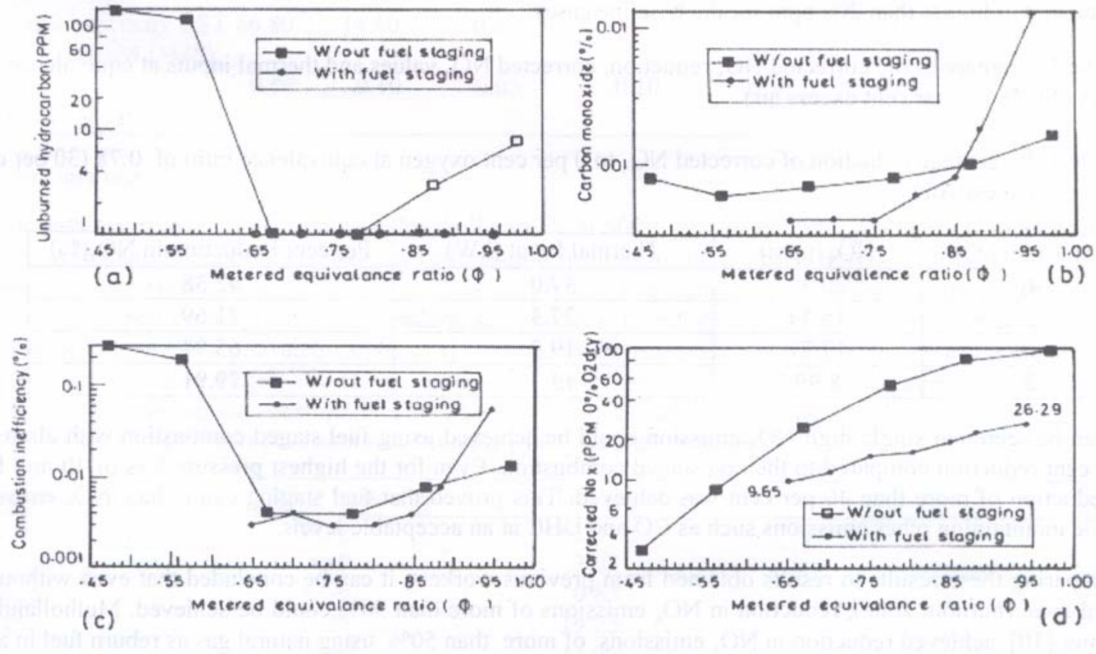

Fig. 5. Mean emissions vs. equivalence ratio for no orifice plate @ ΔP = 20 mm H_2O; T_m = 400 K

Fig. 4d shows an operating equivalence ratio for fuel staged case of 0.655-0.913. The rich condition was limited by a drastic increase in carbon monoxide (CO) emission to an unacceptable value (Fig. 4b). At equivalence ratio of 0.913, a corrected NO_x emission to 0 per cent oxygen on a dry basis of 29.3 ppm were formed representing a 50 per cent reduction. Fig. 4c also shows that a combustion inefficiency of 0.01% was obtainable for a wide range of equivalence ratios up to 0.815 when the combustion inefficiency started to rise. This means that a combustion efficiency of 99.99% was achievable for wide range of equivalence ratios.

Fig. 5-7 show the same trend of results for lower burner pressure losses of 20, 10 and 5 mm H_2O. Reduced pressure loss was obtained by reducing the burner airflow or Mach number, which for the same equivalence ratio reduced the thermal input or modulated the burner power. The operating ranges of equivalence ratios for all cases were around 0.6-0.95. Low NO_x was achieved for all burner pressure losses. Combustion inefficiencies of less than 0.01 per cent were achievable for pressure loss of 20 mm H_2O. However, for pressure losses of 10 and 5 mm H_2O that corresponded to very low airflow rates, showed a higher combustion inefficiency of greater than 0.03 per cent. Even then, combustion inefficiencies of 0.1 per cent were still obtainable for a wide range of equivalence ratios. These correspond to combustion efficiencies of 99.9 per cent.

CO emissions of less than 10 ppm were obtained for all pressure losses over a wide range of EQR up to at least 0.8 prior to rising drastically. This phenomenon (drastic increase in CO emission) may be due to the lack of O_2 in the reburn zone especially at richer condition where all the O_2 was consumed. Less or no O_2 was left to oxidise CO to CO_2. This is because in the present work the third stage air addition burnout zone was eliminated as mentioned in earlier due to rig complexity.

For UHC, at a pressure loss of 20 mm H_2O emission levels of 1 ppm were obtained for almost the entire operating range of EQR except at 0.62, when the emission level was 3 ppm. However, once again, at a lower pressure losses of 10 and 5 mm H_2O, UHC emissions were higher for both cases. Even then, these values are still lower than the baseline values. For most cases, UHC levels of less than 60 ppm were achievable as compared to higher than 200 ppm for the baseline cases.

Table 1 summarises the corrected NO_x reduction, corrected NO_x values and thermal inputs at equivalence ratio of 0.78 (30 per cent excess air).

Table 1: Percentage reduction of corrected NO_x to 0 per cent oxygen at equivalence ratio of 0.78 (30 per cent excess Air).

ΔP (mmH_2O)	NO_x (ppm)	Thermal Input (kW)	Per cent Reduction in NO_x(%)
40	20.32	37.0	42.38
20	15.54	27.3	71.69
10	17.71	19.9	65.94
5	8.99	13.7	79.91

It can be seen that single digit NO_x emission could be achieved using fuel staged combustion with almost 80 per cent reduction compared to the non staged combustion. Even for the highest pressure loss of 40 mm H_2O, a reduction of more than 40 per cent was achieved. This proved that fuel staging can reduce NO_x emissions while maintaining other emissions such as CO and UHC at an acceptable levels.

Comparing these results to results obtained from previous workers, it can be concluded that even without the third zone (burnout zone), reduction in NO_x emissions of more than 50% could be achieved. Mulholland and Lanier [10] achieved reduction in NO_x emissions of more than 50% using natural gas as reburn fuel in a fire

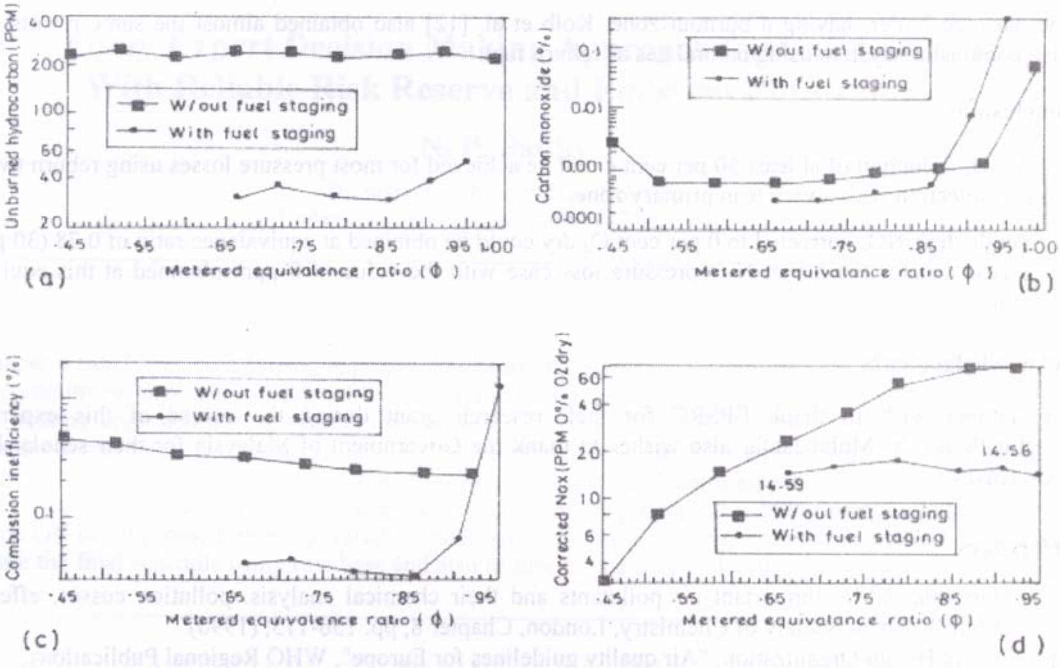

Fig. 6. Mean emissions vs. equivalence ratio for no orifice plate @ $\Delta P = 10$ mm H_2O; $T_m = 400$ K

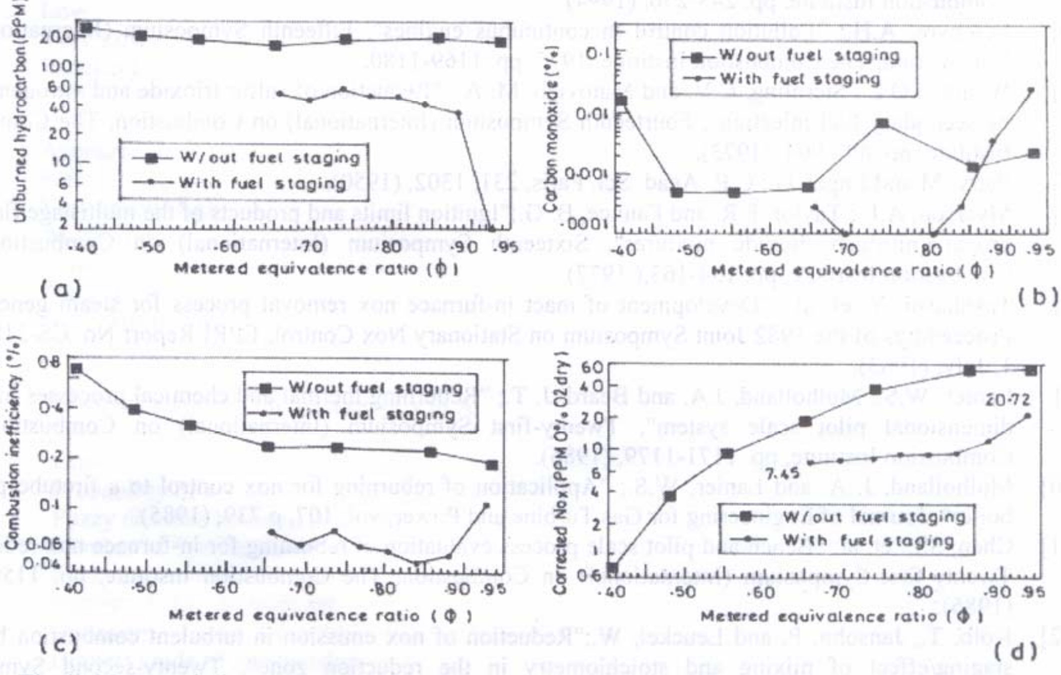

Fig. 7. Mean emissions vs. equivalence ratio for no orifice plate @ $\Delta P = 10$ mm H_2O; $T_m = 400$ K

tube package boiler, having a burnout zone. Kolb et al. [12] also obtained almost the same results using 3 stage combustion system using natural gas as reburn fuel.

Conclusions

- A NO_x reduction of at least 50 per cent could be achieved for most pressure losses using reburn two-stage fuel injection with a very lean primary zone.
- Single digit NO_x corrected to 0 per cent O_2 dry could be obtained at equivalence ratio of 0.78 (30 per cent excess air) for the 5 mm H_2O pressure loss case with the value of 8 ppm obtained at this equivalence ratio.

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