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EFFECT OF AIR-PREHEATING ON NO_x EMISSIONS FROM A GAS TURBINE COMBUSTOR

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ABSTRACT

A 76 mm diameter can combustor equipped with a 45° curved-blade radial swirler was used to study the effect of high inlet temperature gas turbine combustion on NO_x *emission characteristics. High inlet temperature combustion was simulated using preheat air at 400 °K, 600 °K, 740 °K and 900 °K. Natural gas was investigated using passage injection technique. It was demonstrated that increasing the inlet air temperature significantly widened the weak extinction limit and improved the* NO_x *emission characteristics. An optimum* NO_x *emission of less than 4.5 ppm at 15% oxygen, compatible with 99% efficiency was demonstrated at 900 K inlet temperature. It was also demonstrated that with high inlet temperature operation lean well-mixed combustion required for an adequate control of* NO_x *emissions could be achieved. The major conclusion reached is that high inlet temperature combustion could be a promising approach for low* NO_x *emissions with high combustion efficiency and good flame stability.*

INTRODUCTION

As Malaysia moves towards becoming a developed country by the year 2020 more energy intensive industries are expected to emerge over the next 20 years. Consequently there are the needs for more efficient power generation. Gas turbines, in particular natural gas-fired gas turbine systems, will be playing a key role of the next generation of powerplants.

As the demand for electricity increases most powerplants using gas turbine systems will operate at full loads. The need to produce more electricity at peaking service requires the turbine combustor to operate at higher combustion intensity and this can be achieved by increasing the fuel-air mixture strength. In order to increase the air intake the combustor has to operate at high compression ratio. Trend in combustor operating conditions indicates a steady increase in inlet temperature due to increasing compression ratios (1). At high combustion intensity harmful emission products in the exhaust gases consists primarily of oxides of nitrogen (NO_x). NO_x consists of 90-95% NO (nitrogen oxide) and the balance NO_2 (nitrogen dioxide). As a pollutant, NO_x is thought to be harmful in several ways - as a contributor to so-called acid rain, as a destroyer of the ozone layer, and as a heat-trapping compound suspected of increasing atmospheric temperatures. At low elevations, NO also reacts with sunlight to create smog. As the rate of NO_x formation is strongly temperature-dependent any change in flame temperature will certainly affect the levels of NO_x emissions in the exhaust gases. The combustor inlet temperature, to some extent, plays an important role in determining the flame temperature and hence the quantity of NO_x emissions in the exhaust gases. This paper aims to investigate and discuss the influence of high inlet temperature gas turbine combustion from the aerodynamic viewpoint on NO_x emissions using an ultra-low NO_x gas turbine combustor.

OXIDES OF NITROGEN (NO_x)

Oxides of nitrogen which are formed during combustion involving air, commonly referred to NO_x, consist primarily of Nitric oxide (NO) and lesser amounts of Nitrogen dioxide (NO_2).

The Mecahnism of NO_x Formation

Nitric Oxide (NO)

Combustion-generated Nitric oxide (NO) can be formed by three different mechanisms;

(i) *Thermal NO* is formed by oxidation of atmospheric nitrogen in the postflame gases(2). The well established mechanism of NO formation in the combustion processes was suggested by Zeldovich(3). The main reaction governing the formation of NO in fuel lean mixtures is the breakup of the strong triple bond holding N_2 molecule together. This is accomplished by the free oxygen from the equilibrium dissociation of unburnt oxygen molecules which initiate the chain.

ii) *Prompt NO* is produced by high speed reactions at the flame front in hydrocarbon fuels(4). Fenomore(5) showed that NO was formed by enhanced reaction rates as a result of interactions among the many intermediate hydrocarbon species. Claypole and Syred(6) who investigated the influence of levels of swirl aerodynamics on NO_x formation found that the major area of NO^x formation was at the reaction zone in the flame front. The moderate flame temperature and the rapid formation of NO indicated that NO was formed via the promt mechanism.

iii) *Fuel NO* is produced by oxidation of nitrogen contained in the fuel. The fuel nitrogen is converted to HCN in the flame zone (7) and depending on the degree of nitrogen conversions the fuel NO can represent a considerable portion of the total NO. The work of Appleton(8) on vane swirled combustor at atmospheric pressure showed that the degree of fuel/air mixing was a major factor affecting the degree of conversion of fuel nitrgen to NO.

Nitrogen Dioxide (NO_2)

NO_2 which is the major source of atmospheric pollutant is formed by oxidation of NO in the atmosphere. This is because at low temperature NO_2 is more stable than NO. Normally NO_x emissions from combustion processes are dominated by NO. However evidence has shown that NO_2 can be formed in the combustor where a large amount of excess air is present (9).

Operating parameters affecting NO_x formation

The relative importance of the various gas turbine combustor operating parameters affecting NO_x formation has been examined extensively in the past few decades(2-9). The results of these studies have shown that NO_x formation is reaction-rate controlled, a function of flame temperature, residence of the combustion gases, concentration of nitrogen and oxygen present, and to a leseer degree, the combustor pressure. Condition favaourable to NO_x formation are high flame temperature, long residence time, high pressure and high oxygen availability. Flame temperature increases as the rate of reaction increases, and as the primary zone fuel-air ratio approaches the stoichiometric value. Residence time is affected by combustor primary zone length and reference velocities. Insufficient aerodynamic mixing between the fuel and air also encourages the NO_x formation.

EXPERIMENTAL APPARATUS AND TEST PROCEDURES

The atmospheric pressure test rig consists of a 330mm long 76mm diameter uncooled can combustor, air feed blower, electrical air preheater, orifice metering device, 1.5 m long 76mm diameter approach pipe and mean sample probe. There is also a 152mm water cooled exhaust pipe with an observation window on the combustor center line. A schematic layout of the test rig is shown in Figure 1. The combustor was also equipped with wall pressure tappings and thermocouples.

Combustion air and fuel were supplied by an air blower via a 42 mm-diameter orifice meter and a rotameter, respectively. Inlet and outlet, wall temperature and static pressure were monitored by an electronic micromanometer and were recorded in the data acquisition system. The preheat air was introduced in the primary zone through a swirler. The air was heated to the required combustor inlet temperature by an electrical heater. The inlet temperature was measured using a chromel-alumel K thermocouple mounted 100mm upstream the flame stabilizer.

Experimental settings

Air and fuel were partially premixed in the vane passage of a 45° blade angle radial swirler (with a swirl number of 0.54 and a pressure loss of 2.7%) prior to entering the primary zone. The tests were carried out a constant Mach (M) of 0.03. M is defined as the ratio of the mean flow velocity to the velocity of sound, as given by the equation below;

$$M = \frac{V}{\gamma R T} \tag{1}$$

where U is the mean flow velocity in m/sec, R is the gas constant for air in J/KgK, T is the inlet temperature and γ is the specific heat ratio. The Mach number (hence the mean flow velocity), pressure loss (dP/P) and combustor inlet temperature (T) are correlated by the following equation;

$$\frac{dP}{P} = \left(\tfrac{1}{2} R T\right)\left(\frac{U}{C_D}\right)^2 \left(\frac{A_1}{A_2}\right)^2 = \left(\frac{\gamma}{2}\right)\left(\frac{M A_1}{C_D A_2}\right)^2 \tag{2}$$

where A_1 is the upstream pipe flow area, A_2 is the combustor flow area and CD is a flame stabilizer discharge coefficient. The pressure loss is defined as the ratio of pressure drop across of the flame stabilizer to the combustor inlet pressure.

EXPERIMENTAL RESULTS AND DISCUSSION

i) Weak Extinction Results

Weak extinctions were determined at a constant Mach number and pressure loss of 0.03 and 2.7%, respectively and at a preheat inlet air temperature of either 400K, 600K, 740K or 900K by gradually reducing the fuel flow until the flame was finally extinguished. The process was observed directly from the control room through a 100mm diameter observation window. The weak extinctions were also easily observed by a sudden increase in unburnt hydrcarbon (UHC) emissions.

The measured weak extinction results as a function of metred equivalence ratio presented in Figure 2. The test results show that increasing inlet air temperature.from 400K to 900K reduced the weak extinction equivalence ratio from 0.5 to 0.25, thus widening the weak extinction region by 50%. This signifies a continual improvement in the flame stability characteristics as the combustor inlet temperature increases. The reason for this improvement may be explained by referring to equation 3 which correlates the rate of fuel and air mixing, e, taken as equivalent to the rate of energy dissipation per unit mass to the pressure loss parameter and combustor inlet temperature(10).

$$e = C\left(\frac{dP}{P}T\right)^{1.5}\frac{1}{L} \qquad (3)$$

where C = constant $R^{1.5}$, T = inlet temperature and L = integral scale of turbulence.

As the combustor pressure loss was kept constant (and therefore constant turbulence intensity associated with pressure loss and Mach number) increasing the inlet temperature increased the energy of the air jet entering the stabilising shear layers. This resulted in an increase in the shear layer temperature and hence provided a better ignition source and a rapid acceleration of burning velocity of adjacent flame elements within the high temperature stabilizing shear layers. As a consequence the operation was extended to an even leaner mixture.

The above discussion is further supported by the development of combustor wall temperature profiles as shown in Figure 3(a-d). Comparison of temperature shows a steady increase in the rate of flame propagation and the main region of heat release was also much closer to the swirler outlet as the combustor inlet temperature increased. This was mainly due to the reason as discussed earlier.

ii) NO_x Emission Characteristics

Influence of inlet air temperature

i) As a function of Mean Equivalence Ratio

The NO_x/mean equivalence ratio correlation is presented in Figure 4. The minimum vales of equivalence ratio presented here corresponded to the values just priot to lean blowout. The NO_x emissions were at maximum near the stoichiometric value and decreased steadily as the equivalence ratio decreased. As mentioned earlier, the higher inlet temperature operation widened the stability margin considerably allowing operation at a much lower value of equivalence ratio. Consequently, the minimum value of NO_x was somewhat lower for the higher combustor inlet temperature. The lowest value of NO_x for natural gas was 1.4 ppm. This was recorded at the 900K inlet temperature. This figure also shows that increasing the inlet temperature at a constant equivalence ratio caused the NO_x level to increase. The reason for the higher NO_x with higher combustor inlet temperature was mainly due to an increase in the flame temperature (see section ii).

ii) As a function of Flame Temperature

The effect of inlet air temperature on flame temperature and the sensitivity of NO_x emissions to flame temperature are shown in Figure 5 and Figure 6, respectively. The flame temperature is preferable to equivalence ratio as it takes into account any variation in the combustion inefficiency.

As shown in Figure 5 increasing the inlet air temperature at a constant equivalence ratio increased the flame temperature. The combustor primary zone temperature rise, when added to the high inlet temperature flow tends to elevate the flame temperature. An increase in the NO_x emissions with flame temperature as shown in figure 6 was attributed to an increase in the NO_x formation rate because of increasing flame temperature. However, due to the wider flame stability limit with higher inlet temperature, the combustion process was able to operate at an even leaner mixture with a lower flame temperature and hence a significant reduction in NO_x emissions.

Close examination of the flame temperature/NO_x curve in Figure 6 shows that for the same flame temperature the NO_x emissions decreased as the inlet air temperature increased. The reason for the lower NO_x with higher combustor inlet temperature was not only due to the leaner operation but probably also due to the better mixing of fuel and air. The latter may be explained by refering to equation 3; if the pressure loss is fixed constant (as in the case of the present experiment) the rate of fuel-air mixing is strongly dependent on the inlet temperature. The increased energy dissipation rate (hence the mixing rate) with inlet temperature reduced local fuel-rich zones and hence thermal-NO_X forming hot spots. Thus, it can be concluded that low NO_x gas turbine emissions require the fuel injected into the primary zone to burn at a uniformly lean value of equivalence ratio

Comparison of the axial temperature profiles for the same flame temnperature in Figure 3(a-d) indicates that as the inlet temperature increased the main heat release region moved closer to the combustor head. Thus, from a purely flame temperature viewpoint NO_x was most likely to form at the early stage of the combustion process if the combustor inlet temperature is sufficiently high. This may be associated with the combined effects of the unmixedness promoted in the early stage (which give a high equivalence ratio) and the higher inlet temperature (which causes a rapid rise to local flame temperature).

iii) On Combustion Inefficiency

Low NO_x systems are only viable if they are accomplished with low combustion inefficiency. In the present test results the lowest value of NO_x emissions was found just prior to flame blowout, but the combustion inefficiency was unacceptably high. From the practical gas turbine combustion point of view such an operation is not viable.

The combustion inefficiency as a function of the rig metred equivalence ratio is presented in Figure 7. As the inlet temperature increased the inefficiency curves were shifted towards a leaner region and hence allowed the minimum combustion inefficiency at an even weaker equivalence ratio. Such a move was most likely due to the enhanced high temperature unburnt and burnt gas mixing within the recirculation zone which increased the combustion intensity and hence the efficiency of the combustion process.

Figure 8 shows the influence of the combustion inefficiency on the NO_x corrected to 15% oxygen and standard day humidity. As shown in this figure, increasing the inlet air temperature not only improved the efficiency of the combustion process but also decreased the level of corrected NO_x. This shows that high inlet temperature operation could achieve high combustion efficiency without compromising the NO_x emissions. The ultra-low NO_x recorded at the 900K inlet temperature was well within the proposed EPA limit. Thus, high inlet temperature gas turbine combustion could be a promising approach for achieving low NO_x emissions with no associated performance penalty and no adverse effect on flame stability. The highest value of combustion inefficiency was found just prior to flame blowout. A large amount of air present at the leanest mixture may have decreased the mixing shear layer temperature and thereby suppressed the rate of combustion reaction as indicated by the increased UHC emissions.

It is also necessary to accompany low NO_x systems with an acceptable level of Carbon Monoxide (CO) emissions. A correlation of the CO and NO_x emissions corrected to 15% oxygen is presented in figure 9. This figure shows a very similar trend to Figure 8. The minimum CO corrected to 15% oxygen compatible with 0.01% inefficiencies was 7 ppm. Thus, minimum emissions of NO_x and CO corrected to 15% oxygen were simultaneously achieved at a maximum combustion efficiency. The test results also indicate that the minimum combustion inefficiency and CO emissions occurred at the same equivalence ratio.

iv) On NO emission

As has been discussed earlier Nitric Oxide (NO) emitted from a combustion system using gaseous fuel is mainly due to either prompt NO or thermal NO. Figure 10 shows the variation of NO emissions with flame temperature. A comparison of the NO level below 1800 K flame temperature shows a significant reduction in the NO emissions as the inlet temperature increased. Below this flame temperature NO is mainly formed via the prompt NO mechanism(6). The test results also suggest that at the moderate flame temperature high inlet temperature combustion is not significantly influenced by prompt NO. The improved combustion efficiency with inlet temperature may have reduced the intermediate hydrocarbon products in the recirculation zone and hence the NO emissions. Above 1800K flame temperature nearly all the data fall on a straight line indicating that the rate of NO formation is independent of the inlet temperature. The NO emissions beyond this flame temperature, as suggested by Zeldovich(3) is formed via the thermal NO mechanism.

CONCLUSIONS

1. Increasing the combustor inlet temperature significantly widened the weak extinction limit and hence allowed an operation at an even lower value of equivalence ratio.

2. Lean well-mixed gas turbine combustion for low NOx emissions could be achieved by high inlet temperature operation.

3. Ultra-low NOx emissions were achieved along with high combustion efficiency without an adverse effect on stability margin.

REFERENCES

1. **Aircraft Propulsion**. NASA, SP 259, 1971.

2. Bowman, C.T. : **Kinetics of pollutant formation and destruction in combustion**. Prog. Energy and Comb. Sci.., Vol. 11, pg. 33-35, 1978

3. Zeldovich, Y.B. : **The oxidation of nitrogen in combustion explosions.** ACTA Physicohimic, Vol. XXI, No. 6, USSR, 1976.

4. Iverach, Kinov, N.Y. and Haynes, L.H. : **The formation of Nitric Oxide in fuel-rich flame.** Prog. Energy and Comb. Sci.., Vol. 8, pg. 159, 1973.

5. Fenimore, C.P. : **Formation of Nitric Oxide in premixed hydrocarbon flames.** 13th Symposium (Int.) on Combustion. The Inst. of Combustion, Pittburgh, pg. 373-380, 1971.

6. Claypole, T.C. and Syred N. : **The effect of swirl burner aerodynamics on NO_X formation.** 13 th Symposium (Int.) on Combustion. The Inst. of Combustion, Pittburgh, pg. 81-89, 1981.

7. Morely, E.L. : **Formation and destruction of Hydrogen Cynide from atnospheric anf fuel Nitrogen in rich atmospheric pressure flames.** Combustion and Flames , Vol. 27, pg. 189, 1976.

8. Appleton, J.P. and Heywood, J.B. : **The effect of inperfect fuel-air mixing in a burner on NO formation from Nitrogen in the air.** 14 th Symposium (Int.) on Combustion. The Inst. of Combustion, Pittburgh, pg. 777-786, 1973.

9. Lernansky, N.P and Sawyer, R.R. : **NO and NO2 formation in a turbulence hydrocarbon-air diffusion flames.** 15 th Symposium (Int.) on Combustion. The Inst. of Combustion, Pittburgh, pg. 133-136, 1976.

10. Andrews, G.E. and Aboul, M.M. : **High intensity burner with low NO_X emissions.** British Flame Days, 1988.

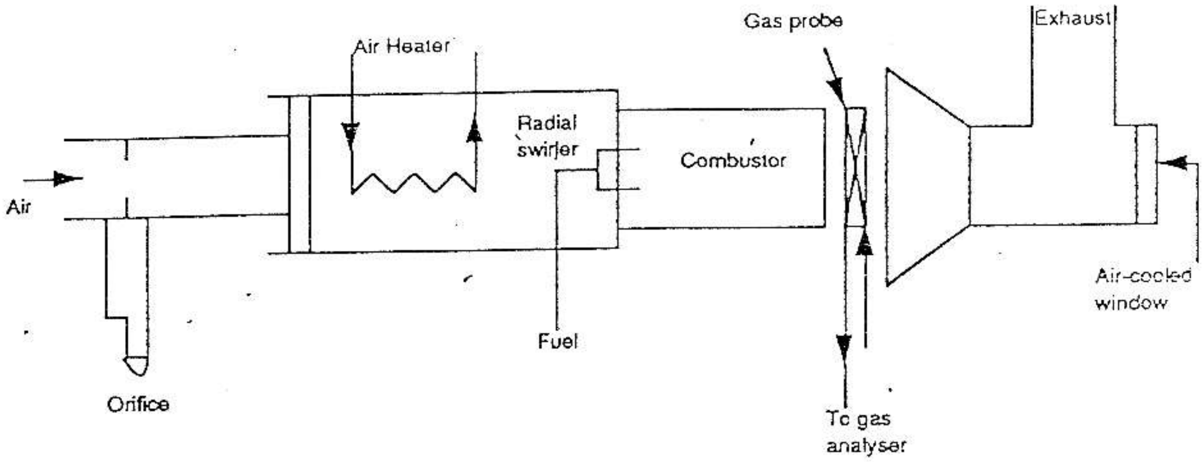


Fig. (1) Schematic diagram of the 76 mm combustion rig

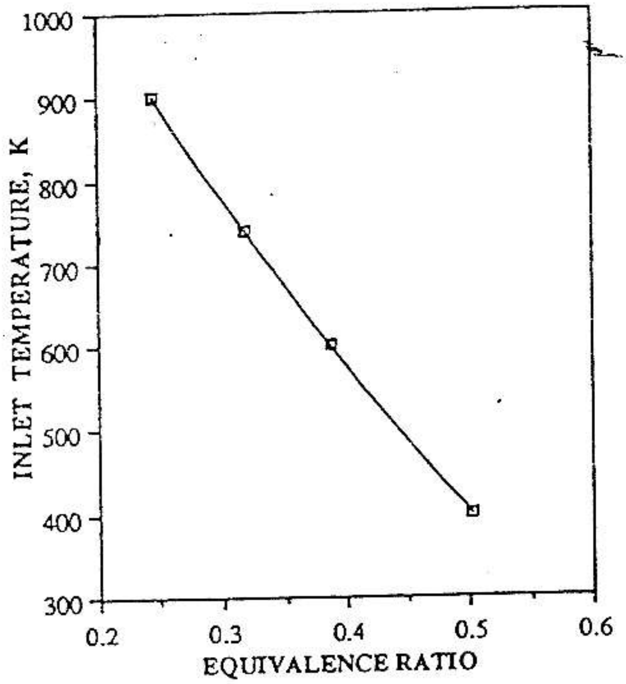
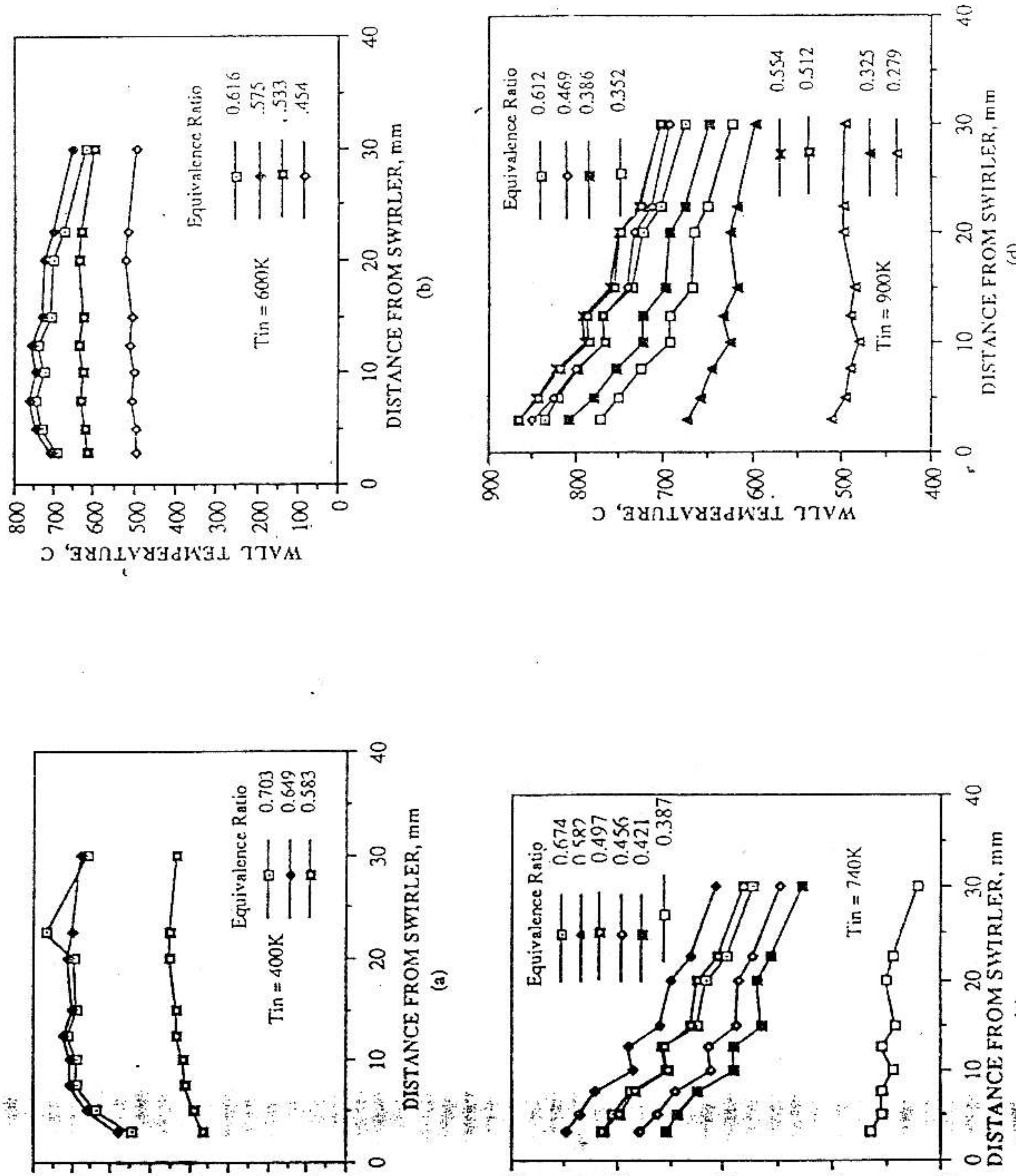


Figure (2): Effect of inlet temperature on equivalence ratio for natural gas combustion



(a) (b) (c) (d)

Fig. (3) Wall temperature profiles for natural gas.

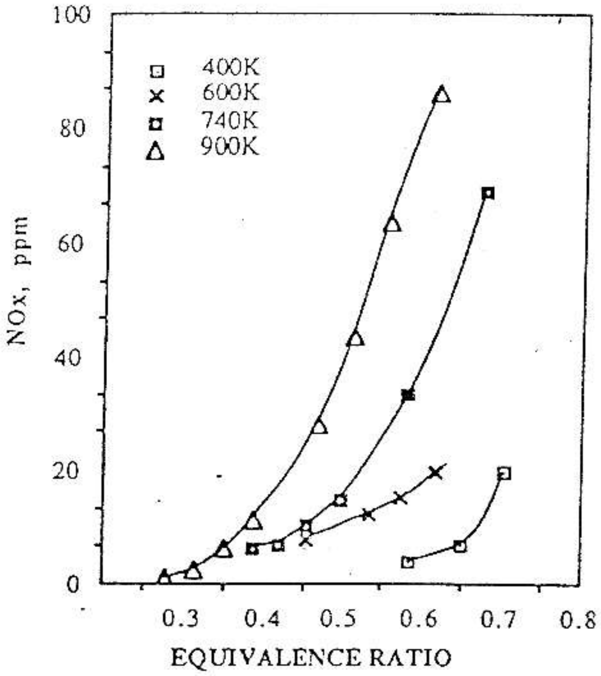


Fig. (4) NOx as a function of equivalence ratio at different inlet temperatures

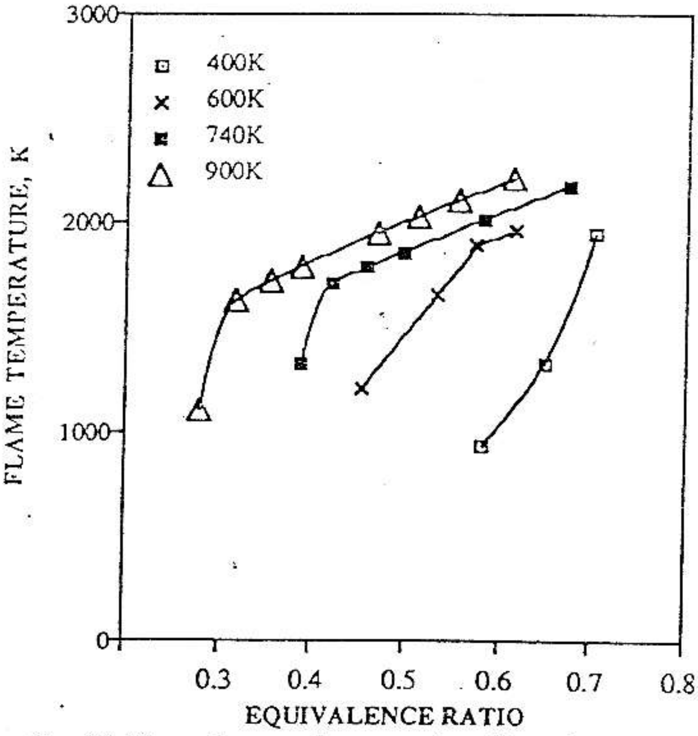


Fig. (5) Flame temperature as a function of equivalence ratio at different inlet temperatures

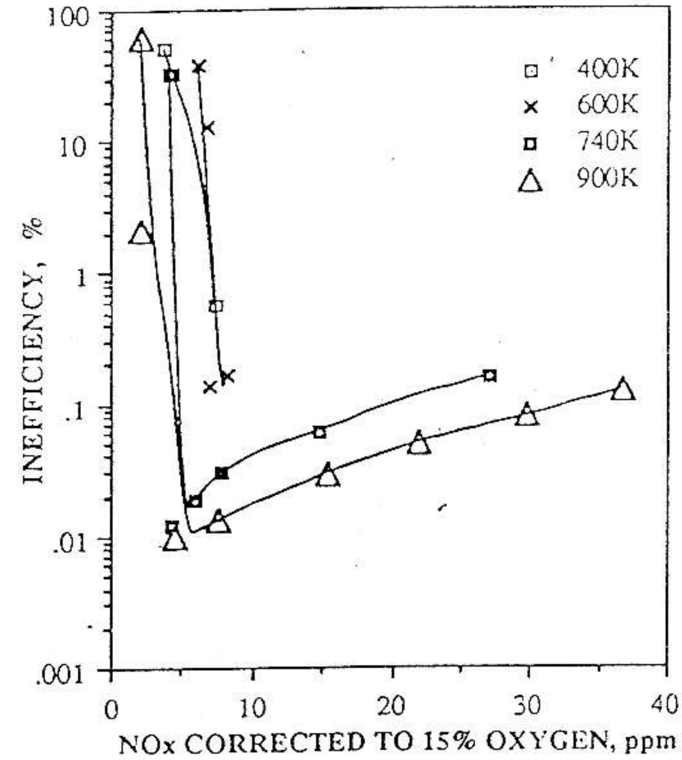


Fig (8): Natural gas combustion inefficiency as a function of NOx corrected to 15% oxygen

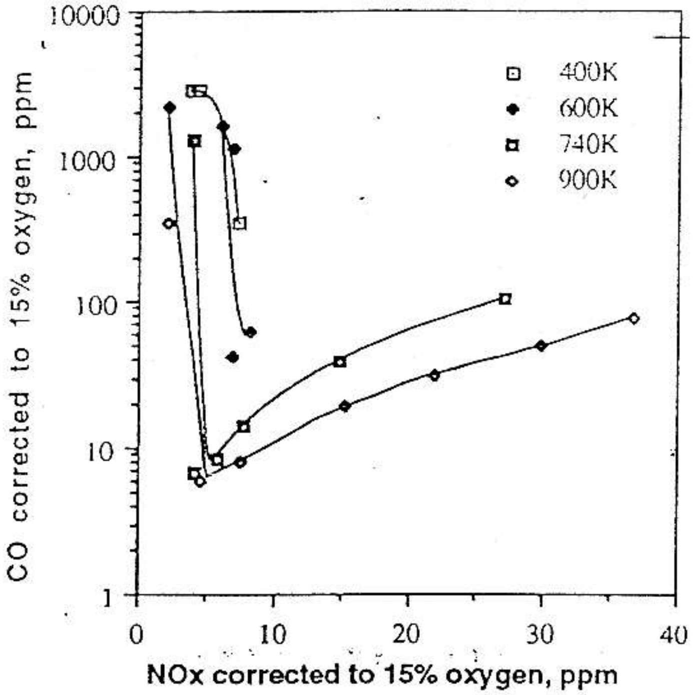


Fig. (9) A correlation of corrected CO and NOx at different inlet temperatures

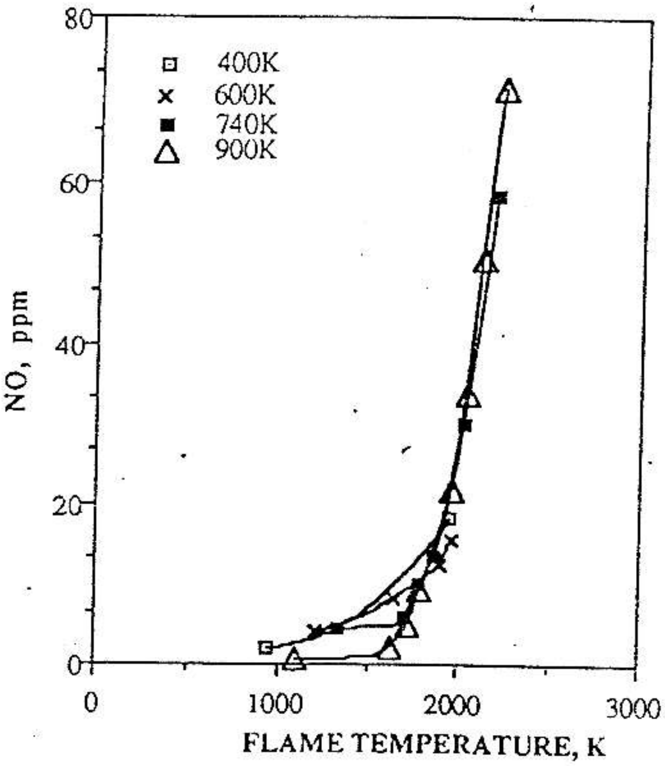


Fig. (10) Nitric Oxide (NO) as a function of flame temperature at different inlet temperatures