Effects of Pressure on Combustion Characteristics of Conical Flameholder

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Abstract

The effects of pressure on combustion characteristics of the conical flameholder were investigated experimentally in the pressure range from 0.11 MPa to 0.40 MPa. The result shows that the total equivalence ratio of lean limit becomes lower as the combustor inlet pressure rises and NOx emission is proportional to the pressure to the 0.5th power.

Introduction

Lean premixed combustion is one of the most attractive methods to reduce NOx emission from gas turbines. However it has a drawback that the equivalence ratio range that can offer stable combustion with high efficiency is very narrow as compared to diffusion combustion. Gas turbine combustors for airplane must be stable in wide operating range. Premixed combustion is not used for gas turbine combustor of airplane because there is no combustion technology that can completely satisfy the demand. The combustor also needs reliability and complicated combustion control and variable geometry system should be avoided. In addition it must be small for economical reason. Combustor using premixed combustion needs fuel mixer and mixing distance that is unnecessary for diffusion combustors. Therefore the distance for combustion must be shorter than the conventional combustor.

At ultra-lean conditions, which are preferable for reducing NOx emission, it is difficult to obtain enough combustion efficiency. The objective of this study is developing a combustor that offers high combustion efficiency, ultra-low NOx emission and stable combustion in wide equivalence ratio range. Various types of flameholders have been studied in lean conditions by Roffe et al.1) The study showed that the type of flameholder has little effect on the NOx emissions. Swirl type flameholder is widely used for gas turbine combustor. It is often used with a pilot burner for stabilization of the flame. But bluff-body type flameholders accompanied by the pilot burner is not studied sufficiently.

A bluff-body type flameholder with pilot burner, which is named conical flameholder, was designed and tested in atmospheric pressure2-4). The study showed that the conical flameholder offers high combustion efficiency at ultra-lean conditions in short combustion chamber and can control oscillatory combustion in high thermal load conditions. As a next step combustion test in conditions of high pressure was started. In this paper the effects of pressure on combustion characteristics of the conical flameholder in the range of combustor inlet pressure from 0.11 MPa to 0.40 MPa were described.

Apparatus and Procedure

Concept of Conical Flameholder

Swirl type flameholder is generally used and is accomplished by diffusion type pilot burner. But it is known that diffusion flame generates much NOx. Therefore premixed type is selected as the pilot flame in this study. Pilot mixture needs higher equivalence ratio than main mixture for stability of the pilot flame. It results higher NOx concentration than that by main flame. It is necessary to reduce the pilot mixture for ultra-low NOx emission. For small gas turbine and gas turbine for airplane, the combustor length must be short. To obtain high combustion efficiency in a short distance at ultra-lean condition, the contact area of main mixture and burned gas generated by pilot burner· must be large. To do that, it is needed to disperse the pilot flame in whole combustion chamber. A bluff-body seems to be efficient to lead the burned gas to radial direction. Based on these facts, the conical flameholder was designed. Figure 1 shows concept of the flameholder. Pilot mixture flows into inside of the flameholder through small holes and forms a stable pilot flame. Burned gas made in the pilot flame runs to radius directions along inner surface of the flameholder. Main mixture flows into through slits made on side of the cone and is ignited by the burned gas.

Flameholder Model and Test Rig

Figure 2 shows the cross-section of combustor with the conical flameholder. This combustor corresponds to one of the six can-annular type combustors for a 4000 kW class gas turbine. Both diameter and depth of the flameholder are 91 mm. The inside diameter of the liner is 142 mm. Two of eight slits for main mixture are longer than the others because of existence of two gas-sampling probes. The struts were modified to give slight swirl to main mixture flow in order to make flow in the combustor stable. The distance from the perforated plate of pilot burner to dilution air hole is 235 mm.

Figure 3 shows the cross-section pressurized combustion test rig with the combustor. The air inlet was connected to electric air heater (600 kW). Exhaust gas turns at right angle at about 0.8 m downstream from the combustor exit. Gas sampling probe was installed about 0.3 m downstream from the corner. The probe was water-cooled and it has 10 sampling holes. The concentrations of 5 chemical species (CO, CO2, Total HC, O2 NOx) are measured by gas analyzer and used to calculate combustion efficiency and the total equivalence ratio.

Test Procedure

Experimental condition is shown in Table 1. The object of this test is to investigate the combustion characteristics of the flameholder. Methane is used as fuel, because the mixing of gas fuel and air is easier than the vaporizing of liquid fuel and mixing with air.

Results and Discussion

Stability limit of pilot flame

To investigate the stability limit of pilot flame, combustion tests were conducted by changing pilot fuel flow rate with no main fuel. Figure 4 shows relations between NOx emissions and the combustion efficiency. The equivalence ratio of pilot burner cannot be known exactly, because the flow rate of air supplied to pilot burner was not measured. But from this figure it is supposed that the equivalence ratio of pilot burner is 0.9 when total equivalence ratio is around 0.045, because NOx concentration in all pressure conditions are highest around this total equivalence ratio. The lean limits were around 0.025 in total equivalence ratio. If it is assumed that the equivalence ratio of pilot mixture is 0.9 when total equivalence ratio is 0.045, the lean limit is about 0.50 in the pilot equivalence ratio. The effect of pressure on the lean limit is not clear from this result.

Figure 5 shows the relations between total equivalence ratio and combustion efficiency in same conditions with Fig. 4. The indigo line and pink line shows the ranges in which the flame attached to the perforated plate were observed in the conditions of combustor inlet pressure of 0.20 MPa and 0.40 MPa, respectively. In these ranges the combustion efficiency has high value. When the pressure is 0.11 MPa, attached flame was not observed. This result shows that the range of stable pilot flame expands as the pressure rises.

Figure 6 shows perforated plate lean stability limit data correlation made by McVey et al.[5] $\Delta P/P_T$ is total pressure loss and q is dynamic pressure at upstream. The formula of the stability parameter is not dependent on the pressure and it means that lean limit is not changed by pressure. This disagrees with the result mentioned above. McVey et al. concluded that the applicability of this correlation to perforated plates should be re-examined. The blue line is drawn based on the conditions and flameholder geometry of this experiment. The total pressure loss of the combustor was 3.6% in the condition of no fuel injection. The lean limit of this experiment agrees with the data in the reference. It shows that the assumption is approximately correct.

Combustion characteristics at total equivalence ratio of 0.30

Figure 7 shows the effect of percentage of pilot fuel flow rate to total one on NOx emissions corrected at 15 % O_2. The total equivalence ratio was fixed to 0.30. In all pressure conditions, the NOx emissions have a maximum value around 13 % and it becomes lower as the percentage goes down. The percentage of lean limit becomes lower as combustor inlet pressure rises. However, these lean limits were higher than the limit of pilot flame without main fuel. The difference was caused by pressure fluctuation that was raised by instability of the main flame. The combustion efficiency was kept high to lean limit in all pressure conditions as shown in Fig. 8. Therefore there is possibility to reduce the NOx emission by shortening the distance from the flameholder to the dilution holes.

Figure 9 shows the effect of combustor inlet pressure on the NOx emissions corrected at 15 % O_2. PP in the figure means percentage of the pilot fuel flow rate to total one. The red line is $y=C\cdot x^{0.5}$, where C is a constant. Lines of all percentage of the pilot fuel flow rate are almost proportional to the red line. It means that the NOx emission is proportional to pressure to the 0.5th power.

Conclusion

The effects of pressure on combustion characteristics of the conical flameholder were investigated experimentally in the range of combustor inlet pressure range from 0.11 MPa to 0.40 MPa at a constant total equivalence ratio of 0.30 and the following conclusions were obtained.

(1) The percentage of pilot fuel flow rate to total one of lean limit becomes lower as the combustor inlet pressure rises.

(2) The combustion efficiency depends on the stability of the pilot flame and stable pilot flame offers combustion efficiency more than 99.9%.

(3) NOx emission is proportional to pressure to the 0.5th power.

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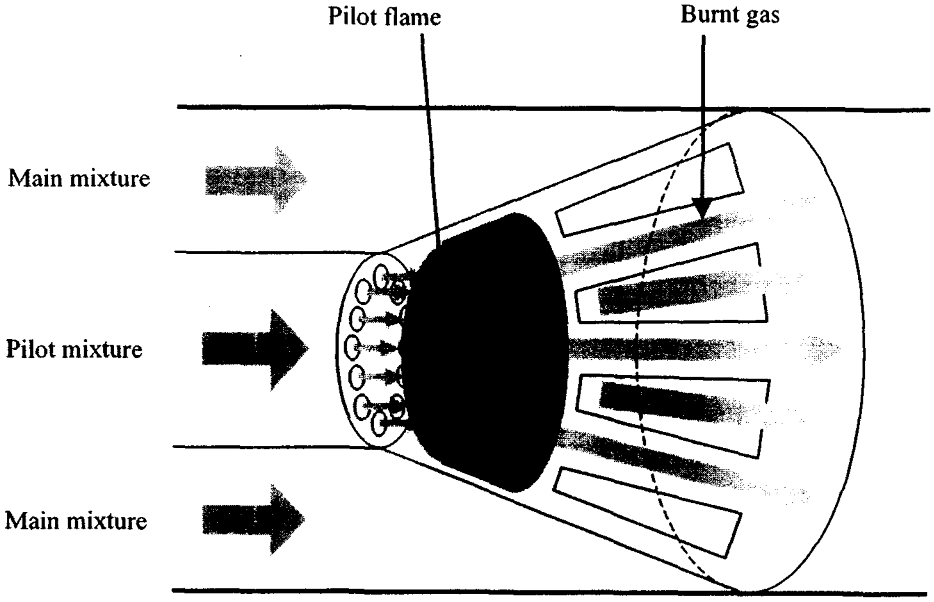

Fig. 1 Concept of conical flameholder

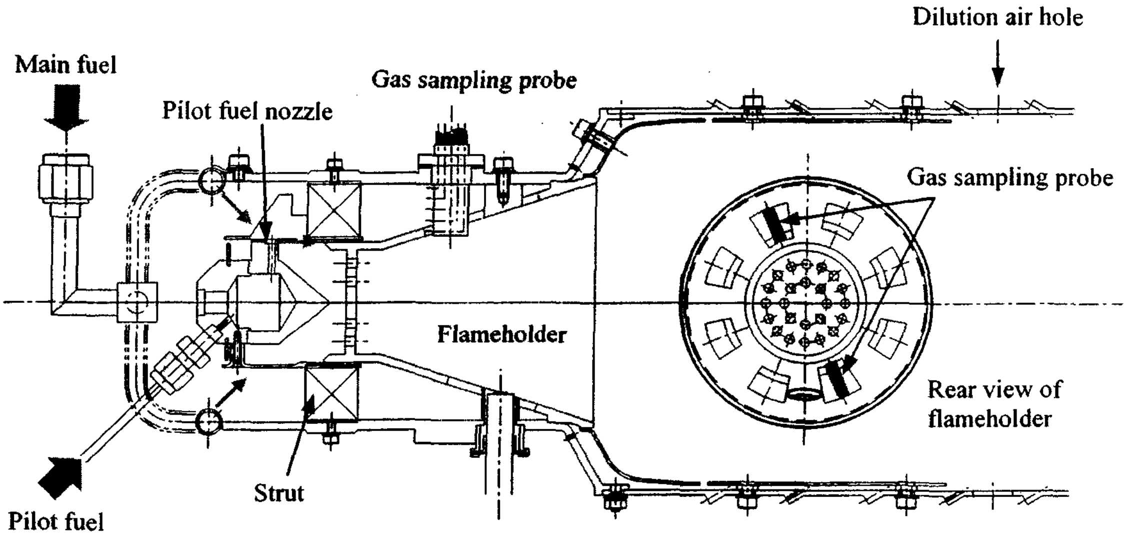

Fig. 2 Cross-section of combustor test model

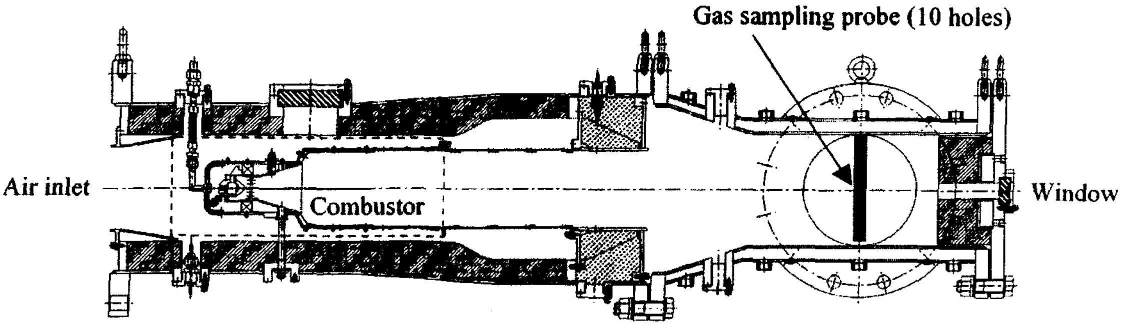

Fig. 3 Cross-section of test rig

Table 1 Experimental conditions

Averaged velocity in combustor liner	25 m/s
Air temperature	616 K
Combustor inlet pressure	0.11 - 0.40 MPa
Pilot fuel flow rate to total one	6 - 17%
Total equivalence ratio	0.02 - 0.30

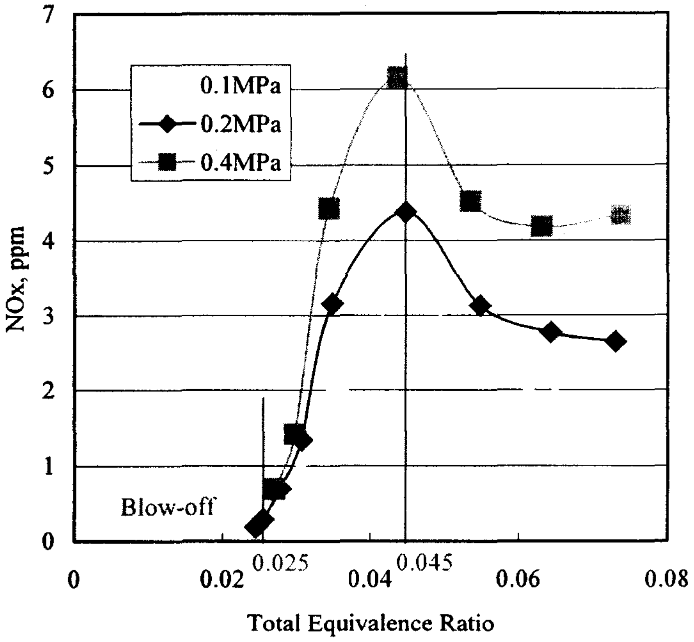

Fig. 4 NOx emission from pilot burner (pilot fuel only)

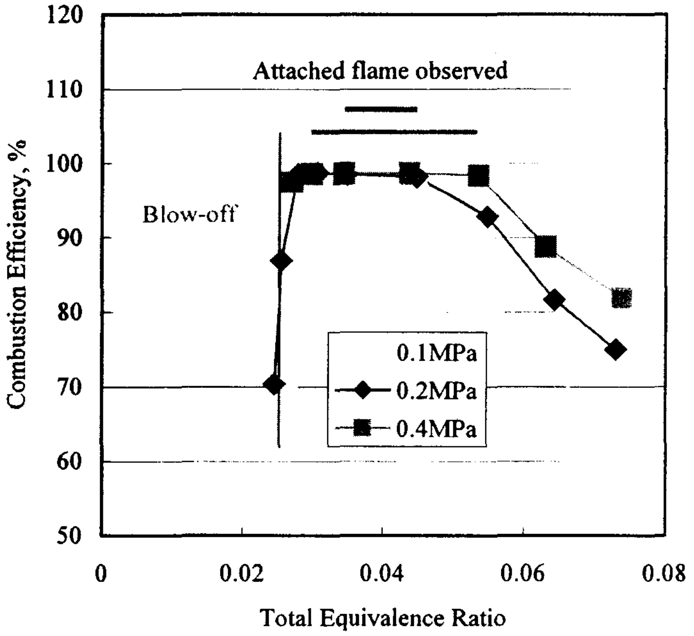

Fig. 5 Combustion efficiency (pilot fuel only)

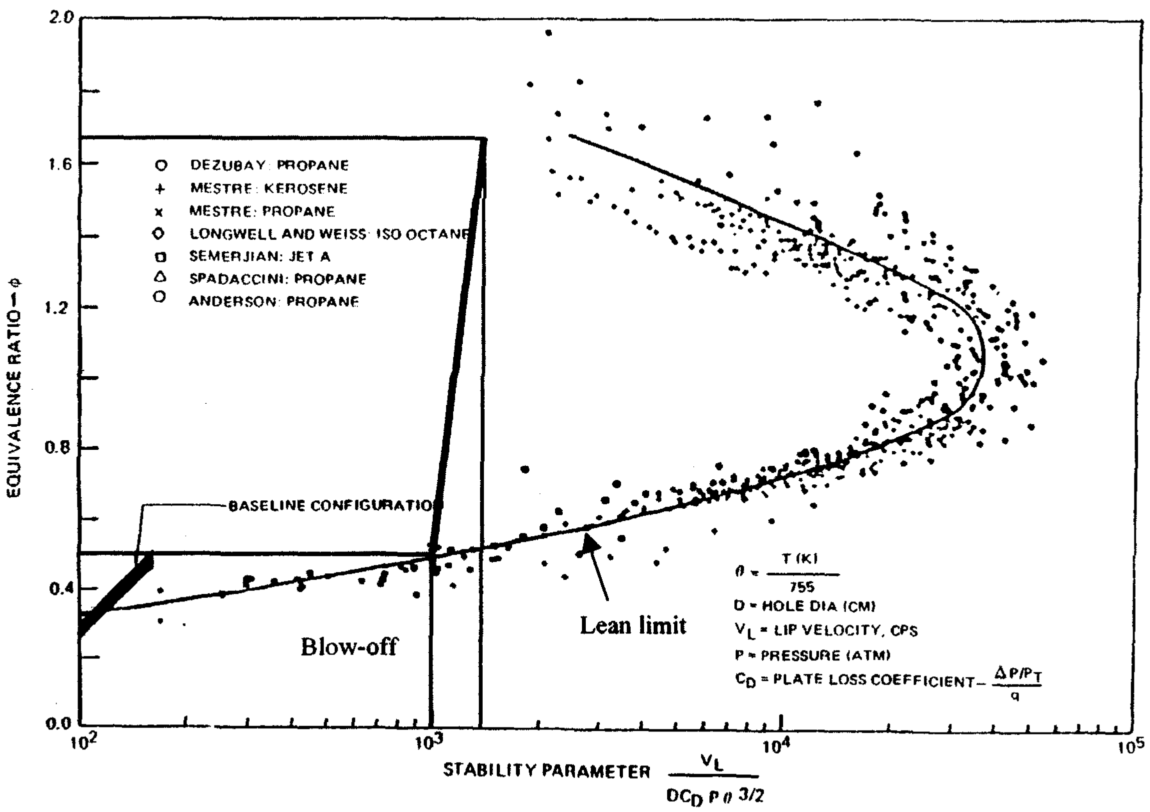

Fig. 6 Perforated plate lean stability limit data correlation[5)]

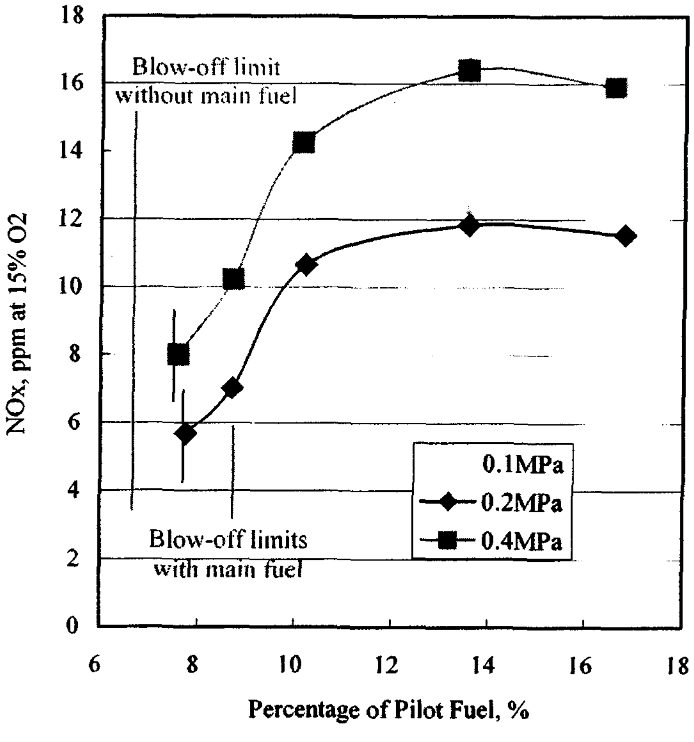

Fig. 7 NOx emission

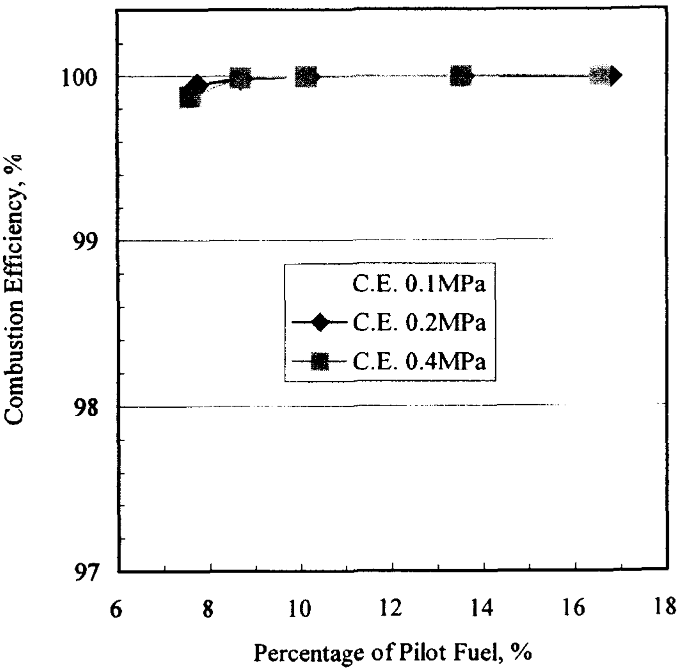

Fig. 8 Combustion efficiency

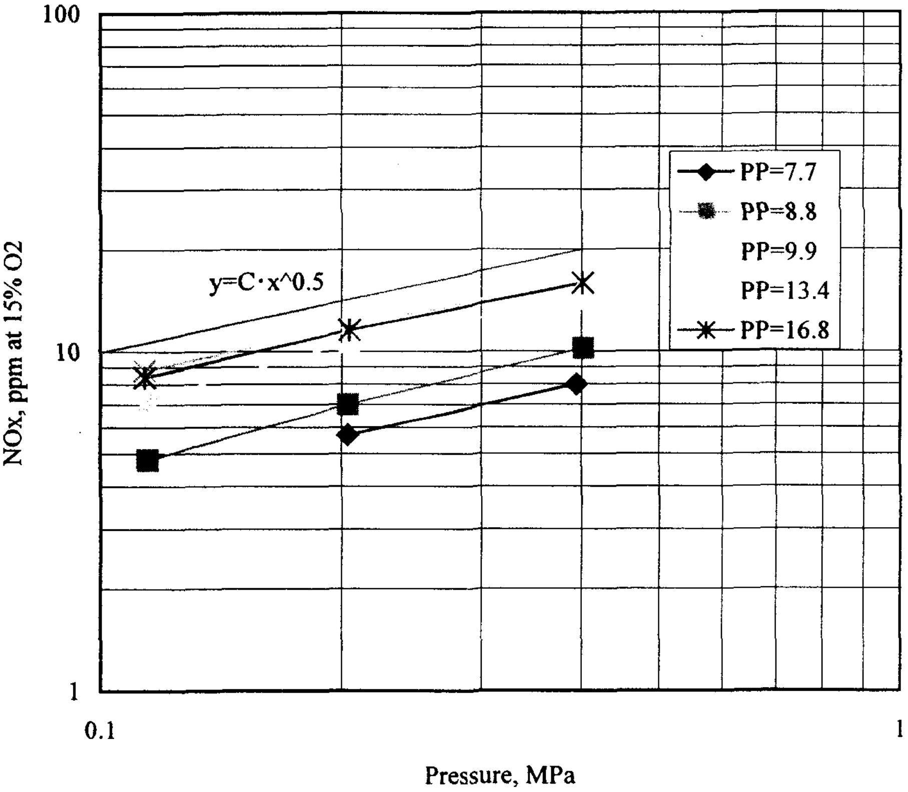

Fig. 9 Effect of pressure on NOx emissions