THE EFFECT OF PRESSURE ON EMISSION INDICES

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ABSTRACT

This paper presents the results of an investigation into the effects of pressure and thermal radiation on NOx emissions from non-premixed turbulent flames in pressures ranging from 1 to 8 atmospheres. Of the three fuels examined, both hydrogen and methane were found to have increasing NOx emissions with increasing pressure. Coincident with the increase in NOx emissions for these fuels was a decrease in the thermal radiation from the flames with increasing pressure. The third fuel tested, ethene, displayed no significant change in NOx emissions with increasing pressure and no significant change in the thermal radiation from the flames with increasing pressure was found. The ratio of NO_2 to NOx emissions was found to decrease with increasing pressure for both hydrogen and methane, but increase with ethene.

INTRODUCTION

The non-premixed, or diffusion flame, configuration is the dominant form of combustion in most practical combustion systems. The products formed from the combustion of the fuel and oxidant often contain unwanted emissions, such as oxides of nitrogen and particulates in the form of smoke. As regulations governing the control of these emissions become more stringent, an understanding of the mechanisms that control the formation of these emissions in combustion systems is necessary.

In the case of emissions of oxides of nitrogen, NOx, from combustion systems, it has been established that there are three mechanisms which bring about its formation; thermal-NO or the Zeldovich mechanism, the prompt-NO mechanism and the N_2O intermediate mechanism (Miller and Bowman). While there have been many studies on the effects of tem-perature on these mechanisms there are few existing investigations into the effect of pressure. Investigations undertaken have examined premixed flame configurations (Drake et al, Drake & Blint, Heberling, Heberling and Boyd, and Reisel and Laurendeau) and these have tended to concentrate on the formation of prompt NO at elevated pressure and the role that super-equilibrium radical concentrations play in enhancing the rate of NOx formation.

In turbulent non-premixed flames, which are similar to gas turbine type combustion, investigations into the effects of pressure on the formation of NOx should include the examination of thermal radiation emissions. Strong radiation sources such as combustion generated particulates in hydrocarbon flames can dramatically reduce the flame temperature and so reduce the NOx emissions formed via the thermal mechanism. If the reduction in temperature is sufficient, prompt NO or N_2O intermediate formation mechanisms may dominate over the thermal mechanism. As pressure is known to increase the rate of particulate formation in hydrocarbon flames, increasing pressure may alter the radiant emissions and so influence the flame temperature. This is apart from any effect that pressure may have on super-equilibrium radical concentrations.

In flames which do not form particulates, like hydrogen where NOx formation via the prompt mechanism cannot occur, the changes in temperature brought about by flame radiation may still be sufficient to influence the formation of NOx.

In this paper we present results of a study into the effects of pressure, and thermal radiation, on the formation of NOx, expressed as an emission index, for a number of fuels burning in a turbulent non-premixed configuration.

EXPERIMENTS

A large high pressure combustion facility has been

Table 1: Experimental Conditions.

Pressure ATM	Nozzle d_n (mm)	H_2 Re=6543 Fr=2.00E6 ■				C_2H_4 Re=16113 Fr=7.55E4 ▲				CH_4 Re=15189 Fr=2.31E5 ●			
		U_f (m/s)	U_a (m/s)	t_r (ms)	L_f (m)	U_f (m/s)	U_a (m/s)	t_r (ms)	L_f (m)	U_f (m/s)	U_a (m/s)	t_r (ms)	L_f (m)
1	3.0	242	0.64	0.012	0.58	47.2	0.65	0.064	0.74	82.5	0.63	0.036	0.74
2	1.9	193	0.48	0.010	0.37	37.5	0.49	0.051	0.47	65.7	0.47	0.029	0.47
4	1.19	153	0.34	0.008	0.23	29.7	0.35	0.040	0.29	52.0	0.34	0.023	0.29
6	0.91	133	0.28	0.007	0.18	26.0	0.29	0.035	0.23	45.5	0.27	0.020	0.22
8	0.75	121	0.25	0.006	0.15	23.6	0.25	0.032	0.19	41.3	0.24	0.018	0.19

constructed at the Aeronautical and Maritime Research Laboratory, Figure 1. The cylindrical pressure vessel is 0.75m in diameter and 3.5m in height with a working section of approximately 1m. It is rated to a pressure of 10 atmospheres. High pressure air is delivered to the vessel from a compressor that supplies upto 5kg of air per second. Inlet mass flow rates are measured by a calibrated venturi. Moisture is removed from the inlet air by dryers. The vessel is fitted with both probe access through side and exhaust ports and optical access through a series of windows. The fuel supplied to the vessel is controlled by calibrated mass flow controllers.
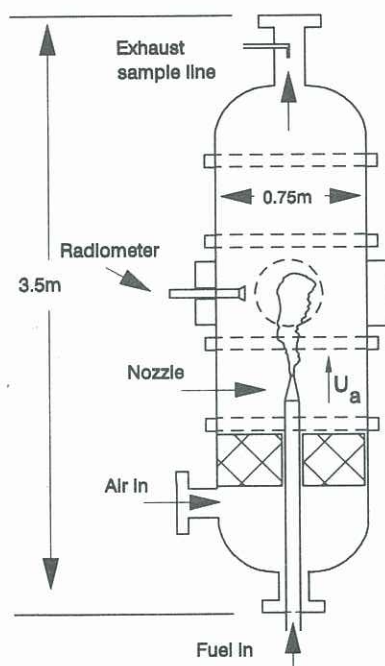

Figure 1: Experimental Facility.

The nozzle used for the flames consists of a central fuel tube surrounded by a number of smaller pilot holes. For the hydrocarbon flames a hydrogen pilot was used to stabilize the flame on the burner. Little variation in the measured emission index was found for large variations in the pilot mass flow rate.

NOx (along with NO and NO_2) concentrations were measured by a chemiluminescent analyser. The measurement sample line was located in the exhaust of the vessel approximately 2.0m downstream of the flame tip, by which time the exhaust gases were thoroughly mixed. The high pressure sample was expanded to atmospheric pressure before connection to the analyser and was well below the dew point for the measurement condition. The measured NOx concentrations are expressed as an emission index defined as,

$$EINOx = \frac{g(NOx)}{kg(fuel)}.$$

Flame radiation was measured by a radiometer (Medtherm 64P-2-22) with a 150 degree view angle. The radiometer was fixed to a moveable probe and located within the pressure vessel. Estimation of radiant heat flux, q_r, from the flames was done using a single point near-field heat flux measurement technique. Emissions are expressed as a radiant fraction, χ_r, of the fuel's enthalpy of combustion, H_c,

$$\chi_r = \frac{q_r 4\pi R^2}{\dot{m}_f \Delta H_c}.$$

Due to limitations imposed by the vessel, the radiometer could not be placed further than 0.45m from the centreline of the flames being measured. For single point measurements such as these, Sivathanu and Gore have shown that a correction needs to be applied to the measured total radiant heat flux when the measurement radius, R, is less than the flame length. A correction technique similar to that of Sivathanu and Gore has been developed and applied to the flames examined here.

RESULTS

The fuels examined in this study were hydrogen (H_2), ethene (C_2H_4) and methane (CH_4). Pressures ranged from 1 to 8 atmospheres. So that the effect of pressure on the formation of NOx can be separated from changes in the flame mixing rates as pressure increases, the flame exit Reynolds ($Re = U_f d_n/\nu$) and Froude ($Fr = U_f^2/gd_n$) numbers were held constant for each fuel. The This results in the following relationships between flame exit velocity, U_f, and nozzle diameter, d_n, with increasing pressure, p,

$$\left(\frac{U_f}{U_{f,i}}\right)^2 = \left(\frac{d_n}{d_{n,i}}\right) = \left(\frac{p}{p_i}\right)^{-2/3}$$

Table 1 shows the results of these requirements for the starting condition of $p_i = 1$ atmosphere and nozzle diameter of $d_{n,i} = 3.0$mm used in this study. Also shown in Table 1 is the inertial time scale for each flame, $t_r = d_n/U_f$, the flame length, L_f, and the Reynolds and Froude numbers for each fuel.
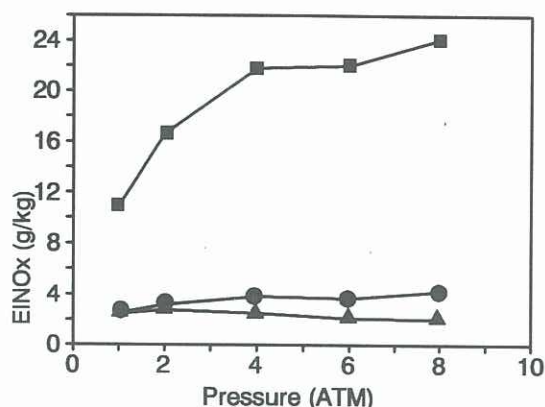

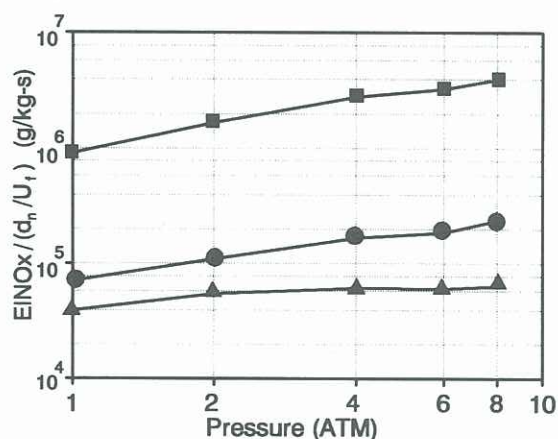Figure 2: EINOX (g/kg) against pressure. Symbols as in Table 1

Figure 3: EINOX/(d_n/U_f) against pressure. Symbols as in Table 1

Results of the measured NOx concentrations, expressed in terms of the emission index EINOx, with increasing pressure for each of the conditions in Table 1 are shown in Figure 2. The emissions for the atmospheric pressure case are similar to those measured by Chen and Driscoll for both the hydrogen and methane flames. Presented in this manner, only hydrogen shows a clear trend with increasing pressure. To remove the effect of decreasing residence time, t_r, with increasing pressure, Figure 3 shows the emission indices normalized by the inertial time scale. The normalized emission indices shown in Figure 3 for both hydrogen and methane show a clear trend of increasing NOx emissions with increasing

pressure. For hydrogen the EINOx/(d_n/U_f) varies as pressure to the power of 0.7, while for methane it varies as 0.6. In contrast to the results for hydrogen and methane, ethene appears to show minimal increase in NOx emissions with increasing pressure.
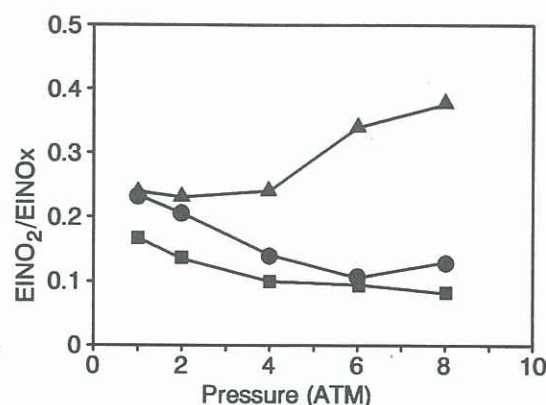

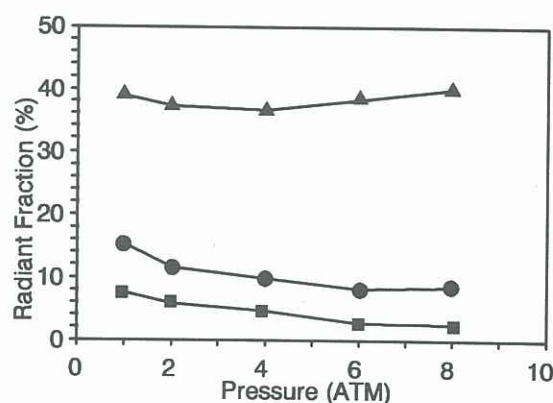Figure 4: EINO$_2$/EINOx against pressure. Symbols as in Table 1

Figure 5: Radiant fraction against pressure. Symbols as in Table 1

Figure 4 shows the ratio of NO$_2$ to NOx emissions for each flame against increasing pressure. All fuels show significant proportions of NO$_2$ for the atmospheric condition which decrease with increasing pressure for the hydrogen and methane, but increase with increasing pressure for the ethene.

The radiant fractions for the fuels are shown in Figure 5. Both hydrogen and methane display decreasing radiant fractions with increasing pressure, while ethene appears to yield an almost uniform radiant fraction independent of pressure and significantly higher than the other fuels. The higher radiant fraction for ethene is expected as this fuel has a greater propensity to form soot which is the main source of radiant emission in these hydrocarbon flames.

The effect that the radiant emissions have on the peak flame temperature can be estimated by adjusting the calculated adiabatic stoichiometric flame temperature, based on equilibrium calculations (Kee et al), by an amount equivalent to the energy lost by

radiation. This estimate is shown in Figure 6 for the three fuels. It can be seen that while ethene has a higher adiabatic flame temperature than methane, (T_{AD}=2369K, for ethene; T_{AD}=2226K for methane, at 1ATM) the higher radiant emissions in these flames result in the peak flame temperature for ethene being significantly lower than methane for all conditions; this difference increases with increasing pressure. Hydrogen, in keeping with its low radiant fractions and relatively high adiabatic flame temperature (T_{AD}=2383K, 1 ATM), shows the highest adjusted flame temperature which increases with increasing pressure.

The effect of increasing peak temperature on the NOx formation rate in the hydrogen flames can be estimated by comparing the increase in the measured normalised NO emission index to that calculated by assuming that the O + N_2 (E/R=-38000K) reaction is the rate controlling step in the thermal NO formation mechanism. For the temperature increase shown in Figure 6, the NO formation rate is calculated to increase by a factor of around 2.5 as the pressure increases from 1 to 8ATM. For the same pressure increase, the measured increase in NO emissions is around 4.5. The sensitivity in the estimation of the peak flame temperature is such that a 10% increase in the radiant fraction of the 1ATM hydrogen flame will increase the calculated ratio from 2.5 to 3.
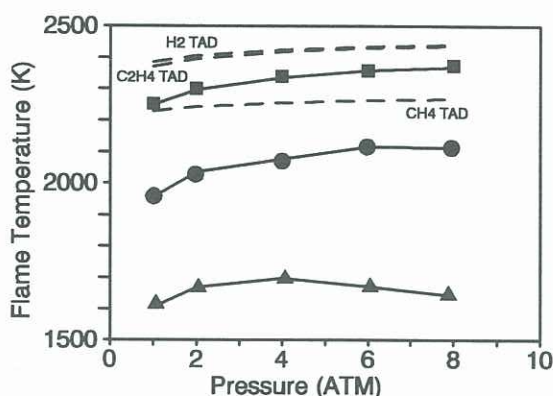

Figure 6: Calculated peak flame temperature against pressure. Symbols as in Table 1, dashed lines represent adiabatic flame temperature

The effect of increasing temperature on the production of NOx in the methane flames is not clear. For the temperatures shown, the NO formation via the prompt route is expected to be significant and perhaps dominant for the cooler lower pressure flames. This will certainly be the case for the ethene flames. It is worth noting, however, that coincident with an increase in estimated peak flame temperature, the formation of NOx in the methane flames increases, while static peak temperatures in the ethene flames coincide with static NOx emissions.

CONCLUSION

Measurements of the NOx emission index for hydrogen, methane and ethene turbulent non-premixed flames at constant Reynolds and Froude numbers were obtained at pressures ranging from 1 to 8 atmospheres. For both the hydrogen and methane flames, the NOx emission index normalized by the inertial time scale of the flame increased with increasing pressure. For hydrogen the normalized NOx emission index increased at the rate of pressure to the power 0.7, while for methane the pressure exponent was found to be 0.6. No increase in NOx emissions for the ethene flames was observed.

Measurements of the radiant emissions from the flames, expressed as a radiant fraction of the flame combustion energy, were found to decrease with increasing pressure for hydrogen and methane, but remain uniform for ethene.

The ratio NO_2 to NOx emissions was found to decrease with increasing pressure for the hydrogen and methane flames, but increase for the ethene flames.

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