Effects of wall temperature and gas on ducted premixed flames

By E Korusoy and J H Whitelaw,
Department of Mechanical Engineering,
Imperial College, London SW7 2BX

ABSTRACT

Experiments with mixtures of air and methane, propane and ethylene in a round duct, with the flames stabilised on a sudden expansion and an open downstream end, show the dependence of flammability and stability limits and the amplitude and frequency of oscillations on the gas and the wall temperature. Thus, the lean limit at a Reynolds number of 39,500 varied from equivalence ratios of 0.64 to 0.5 with methane and a cold and hot wall respectively and from 0.48 to 0.33 with ethylene. The results with propane were closer to those with methane. The cold-wall temperature was around 300 K while the maximum temperature of the hot wall was just under 1000 K. These results are in accord with the relative flame speeds of the three gases. The corresponding limits at which the rms of pressure oscillations transitioned from low to high values depended on the gas and Reynolds number, rather than the wall temperature, and the locus of the region of instability occurred at equivalence ratios of 0.68, 0.82 and 0.85 with ethylene, propane and methane, respectively at the Reynolds number of 39,500 corresponding to energy release rates of 150, 167 and 170 kW.

Pressure signals quantified the amplitude and frequency of oscillations associated with strain rates and acoustic and longitudinal acoustic modes. The former were more prominent with the lower flame speeds where high strain rates close to the expansion plane caused extinction with subsequent re-light at the lower strain rates of the downstream flow. Maximum peak amplitudes of up to 1 and 10 kPa were measured with methane and ethylene respectively as overall extinction was approached and extinction-and-relight coupled with acoustic frequencies. The rms of pressure fluctuations with methane was less than 1 kPa in the range of stable flow before increasing with equivalence ratio to 4 kPa at stoichiometry. Acoustic frequencies dominated in this region and were determined by the chosen upstream and downstream duct lengths. Rms amplitudes were affected by gas so that, with ethylene, competition between a three-quarter wave in the upstream duct and a three quarter wave in the entire duct limited amplitudes to around 1 kPa at stoichiometry. Thus, the effect of gas was small in the vicinity of the stability limit but the increasing difference between methane and ethylene towards stoichiometry was due to increased excitation of the upstream ¾ wave of ethylene, which was incompatible with the ¾ wave of the entire duct, the upstream mode requiring a pressure node at the expansion plane and the latter a pressure antinode. Duct wall temperature also had an effect on rms amplitudes and values for methane flames at stoichiometry decreased from 4 to 1 kPa as the temperature increased from less than 400 K to over 900 K.

Attempts to control the oscillations with imposed oscillations, active control and small quantities of fuel at the sudden expansion are described and quantify the relative advantages and limitations, the latter due to the acoustic signals that were always modulated by low frequencies, probably associated with extinction and relight.

Flow configuration, instrumentation and control devices

The duct was similar to that used by Emiris and Whitelaw (2003) and is shown on figure 1.It comprised an upstream section 51 mm in diameter and 1060 mm long and the part downstream was 80 mm in diameter and 934 mm long with an open end. A swirl generator, in which the gases were premixed, closed the upstream end and a length of honeycomb subsequently removed the swirl. The flames stabilised on the sudden expansion, provided by the different diameters of the two parts of the duct, and the downstream end was open. The ambient temperature of the reactants upstream was around 300 K while the products downstream were hotter, leading to a shorter acoustic length. Thus, the lengths of the two ducts were chosen so that the half-wave frequency upstream approximately matched the quarter-wave downstream (the latter with an assumed average product temperature of 1200 K) and this ensured that the dominant frequency was equal to the duct ¾ wave at about 170 Hz. The rms amplitude of the pressure fluctuations did not exceed around 4 kPa and were limited by the maximum Reynolds numbers and heat-release rates of the three fuels, as well as by the duct wall temperature discussed further in the results section below. Part of the downstream duct was replaceable with a modified section including a quartz window to allow visualisation of the step region.
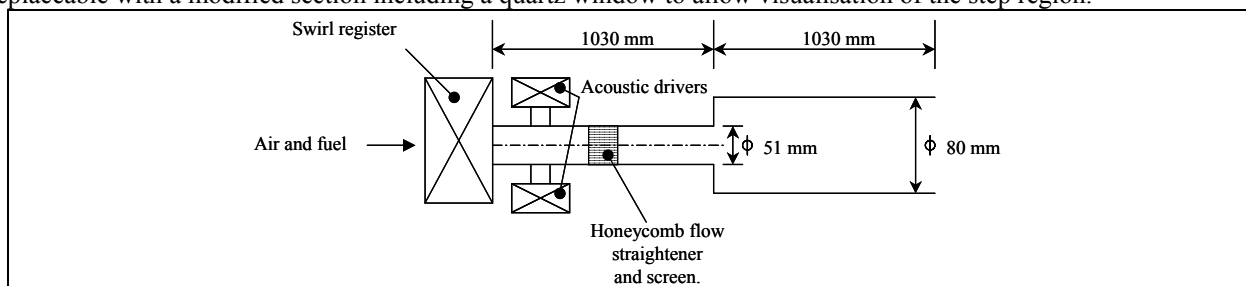

Figure 1: Round sudden-expansion configuration with acoustically closed upstream end and facility for oscillating pressure field. Not to scale. All dimensions in mm.

The bulk flows comprised mixtures of air and methane (94 % pure), propane (96 % pure) and ethylene (99.9 %), premixed far upstream of the expansion plane in the swirl register, which also provided an acoustic impedance of unity. Screens after the honeycomb ensured well-mixed two-dimensionality of the flow at the expansion plane after the swirl was removed. The flow rates were regulated to a precision of 3 % by calibrated float-rotameters (Rotameter Manufacturing Co. and KDG Instruments) and the mass-flow rates through the combustor are presented in terms of the Reynolds number based on the bulk velocity and upstream duct diameter.

Pressure fluctuations were measured with a water-cooled piezo-electric transducer (Kistler 6121 and charge amplifier 5007) mounted flush with the pipe wall 70 mm upstream of the expansion plane with the signal supplied through an interface (National Instruments DAQ BNC-2090 and PCI MIO 16E4 A/D card) to a computer for acquisition (LabView software) of 8 seconds of data per condition at a sampling rate of 4096 Hz. Post-processing of the pressure signal involved custom written software (C++) and implementation of a recursive Fourier analysis algorithm using the Hanning function with each data interval of 1 s and 50 % overlap to give a resolution of 1 Hz. The duct wall temperature was measured with Pt-Pt/13 % Rh but-welded thermocouples of wire diameter 200 microns placed in contact with the wall surface at positions from 100 mm upstream to 1000 mm downstream of the expansion. Gas temperatures were also measured with similar thermocouples on the centerline at the step, position of maximum duct wall temperature and at the duct exit.

Acoustic control was achieved with passive and active imposed oscillations and small quantities of fuel added upstream of the expansion plane. The passive control system involved a function generator (Derritron TA120) and acoustic drivers (Naigara, NAS-813-22) with coupling between the imposed and naturally occurring oscillations maximised by placing the actuators close (within 70 mm) to the pressure antinode located at the acoustically closed upstream-end of the duct. The maximum electrical input power to the drivers was 51 W and their acoustic power output depended on the coupling between the imposed frequency and the acoustic characteristics of the duct so that it was a maximum near the harmonics of the ¾-wave. The active feed-back system comprised a band-pass filter from 160 to 180 Hz (Krohn-Hite Model 3202) with a custom-built phase locked loop to produce an output signal that was frequency and phase-locked to the dominant mode of the duct and fed back with variable phase-delay through a custom built stereo amplifier to the acoustic drivers that caused destructive or constructive interference. Small quantities of fuel (2 to 5% of the total fuel flow) were injected through four evenly spaced injectors 60 mm upstream of the expansion and provided an alternative means of passive control.

Results

The results are presented in four sections dealing with visualisation, lean extinction and the effects of wall temperature, stability limits and the nature of oscillations, and control.

Visualisation

The quartz widow was used to observe the step and photographs showed the mean luminosity and its distribution for lean methane- and ethylene-air flames at identical conditions and that methane-air flames stabilised approximately 4 step-heights downstream of the expansion while ethylene flames were in contact with the step and partially distributed upstream along the expansion plane. Similar observations with propane showed that, as with methane, stabilisation occurred downstream of the expansion with no distribution of heat-release upstream.

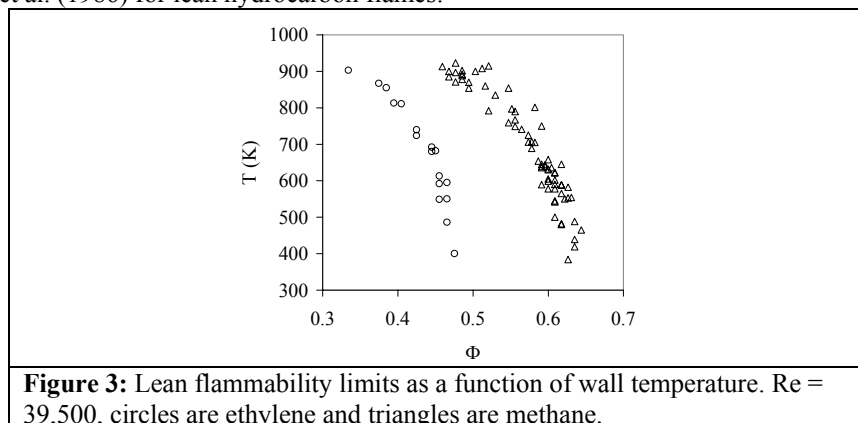### *Lean extinction and the effects of wall temperature*

A typical profile of mean temperature along the duct wall at equilibrium is given in figure 2, which shows a sharp increase from a minimum of less than 300 K at 10 cm upstream of the expansion, to a maximum of 950 K 34 cm downstream, after which there was a gradual decline towards the open end of the duct. The maximum in temperature downstream of the expansion was expected from the photographs, which showed that the flame stabilised in this region and the sharp drop in temperature further upstream was a consequence of heat loss to the oncoming cold reactants. The products were hot and the rate of cooling was much slower downstream of the temperature peak.

Figure 2: Profile of wall temperature at thermal equilibrium, Methane-air , Re = 39,500, ϕ = 0.89, X = distance downstream of the expansion.
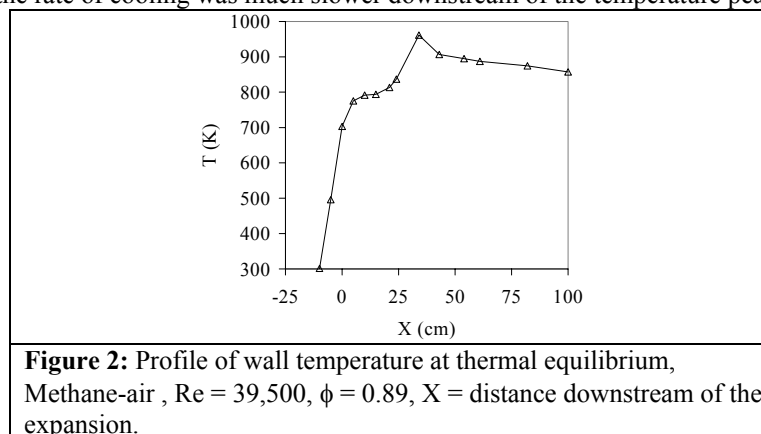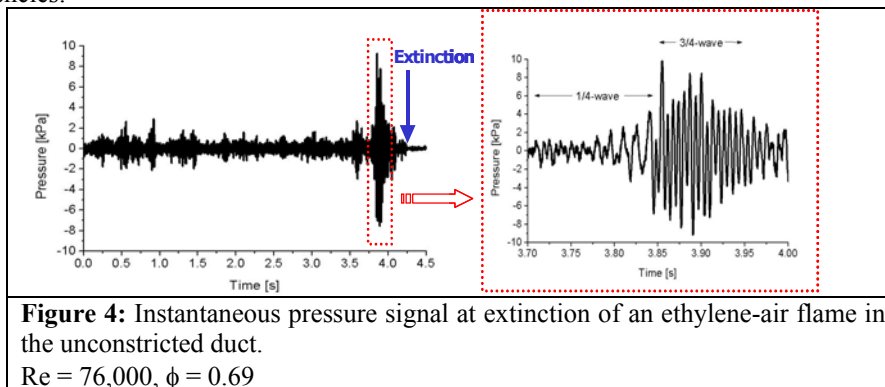
The flame temperature varied with equivalence ratio and this was reflected in the peak temperature at equilibrium, which was almost 1000 K with near-stoichiometric mixtures, but less than 700 K near the lean extinction limit. The temperature distribution was uniform at around 300 K at start-up conditions and increased with time until equilibrium was established after about 10 minutes. The flame extinguished at equivalence ratios that depended on the maximum wall temperature, as shown in figure 3 for mixtures of air and, methane and ethylene. The burner was operated at stoichiometric conditions until the desired temperature was reached, after which the fuel flow rate was reduced quickly and the temperature at extinction noted. Sample measurements with propane-air mixtures showed results slightly to the left of those with methane and with similar curvature.

The figure shows that the lean limit at a Reynolds number of 39,500 varied from equivalence ratios of 0.64 to 0.5 with methane and wall temperatures from 400 to 900 K respectively and from 0.48 to 0.33 with ethylene and the same increase in temperature. At any given temperature, the lean extinction limits were smallest with ethylene and largest with methane and this is qualitatively comparable to the faster flame speeds of ethylene. The change in the equivalence ratio of lean extinction with increase in temperature is not surprising since flame speed decreases with equivalence ratio

and increases with temperature and it is likely that partial pre-heating was responsible for the increasingly lean extinction limits. It is also evident that lean extinction occurred in ethylene at the equivalence ratio of 0.48 and cold operating conditions while methane extinguished at the same equivalence ratio under hot operating conditions. It should be noted that, regardless of temperature, extinction did not occur above a critical equivalence ratio, 0.48 with ethylene and 0.65 with methane. Similarly, provided the equivalence ratio is not zero, extinction is not expected to occur above a critical temperature and this is consistent with the curvature of data in figure 3 and with the limit temperature of 1200 K suggested by Law et al. (1986) for lean hydrocarbon flames.

Figure 3: Lean flammability limits as a function of wall temperature. Re = 39,500, circles are ethylene and triangles are methane.

The process of extinction at any point of the curves of figure 3 was similar with low frequency amplitude modulations of the dominant mode and increasingly high peak-to-peak values as it was approached, particularly at high Reynolds numbers and with low wall temperatures where a large modulation was often followed immediately by extinction. De Zilwa et al (2001) observed the same phenomenon with methane and hot operation showed peak amplitudes of the order of 1 kPa immediately prior to extinction in a round duct without constriction. It was also evident that the peak amplitudes of the modulation and acoustic pressure signals were up to 5 and 10 kPa respectively with an exit nozzle, occurred immediately prior to extinction and due to coupling between the cyclical extinction-and-relight and a bulk mode oscillation at around 35 to 50 Hz. In the present experiments with an open downstream end and three fuels, there were similar modulations in amplitude close to extinction and figure 4 shows an explosive modulation of peak amplitude around 10 kPa in the pressure trace of an ethylene-air flame after 4 seconds of data collection and lasting 200 ms, after which it extinguished. In this case, there was an increase in the peak amplitude of the upstream ¼ wave (at around 80 Hz) from 2 to 4 kPa over 50 ms after which there was a sharp transition to the ¾ wave of the entire duct (175 Hz) so that the coupling was between two acoustic frequencies rather than between acoustic and extinction-and-relight frequencies.

Figure 4: Instantaneous pressure signal at extinction of an ethylene-air flame in the unconstricted duct.
Re = 76,000, ϕ = 0.69

The change in the dominant frequency in near-limit ethylene flames contrasts with that of methane or propane where it remained constant and was modulated only in amplitude by extinction-and-relight. The different behaviour may be explained by the higher speed of ethylene flames, and the photographs showed that they stabilised close to the step with a propensity to flash upstream, while methane or propane-air mixtures stabilised further downstream and did not influence the upstream region. Extinction did not occur with higher equivalence ratios but the region of stable low-amplitude combustion ended at the lean stability limit, where a small increase in equivalence ratio led to a large increase in the rms of pressure fluctuations.

Stability limits and the nature of oscillations

The locus of the region of instability was dependent on the fuel type and occurred at increasing equivalence ratios with ethylene, propane and methane, namely 0.68, 0.82 and 0.85 respectively at the Reynolds number of 39,500 and this corresponded to similar energy release rates of 150, 167 and 170 kW that were within 8 % of the average value of 162 kW. Thus, since an increase in Reynolds number increased the rate of combustion and hence the power of the flame, the lean and rich stability limits moved further from stoichiometry. Since the stability limits were unaffected by wall temperature, they are probably unrelated to extinction.

Figure 5 shows the flammability and stability limits for methane and ethylene together with profiles of the normalised rms of pressure fluctuations. As discussed previously, very lean mixtures led to extinction while large-amplitude oscillations occurred with intermediate values and, with excessively rich mixtures, the methane flame at the step blew off to form a partially premixed flame stabilised at the open end of the duct. At Reynolds numbers greater than 60,000, the methane partially premixed flame led to excitation of the full-wave frequency of the entire duct and

amplitudes well in excess of 10 kPa. The rich flammability limit shown for ethylene corresponds to the equivalence ratio at which the flame blew off at the step, and acoustic generation from the downstream flame occurred at Reynolds numbers over around 50,000. Thus, the rich flammability limit was difficult to quantify and the rich-limit results of figure 8 should be regarded as approximate.
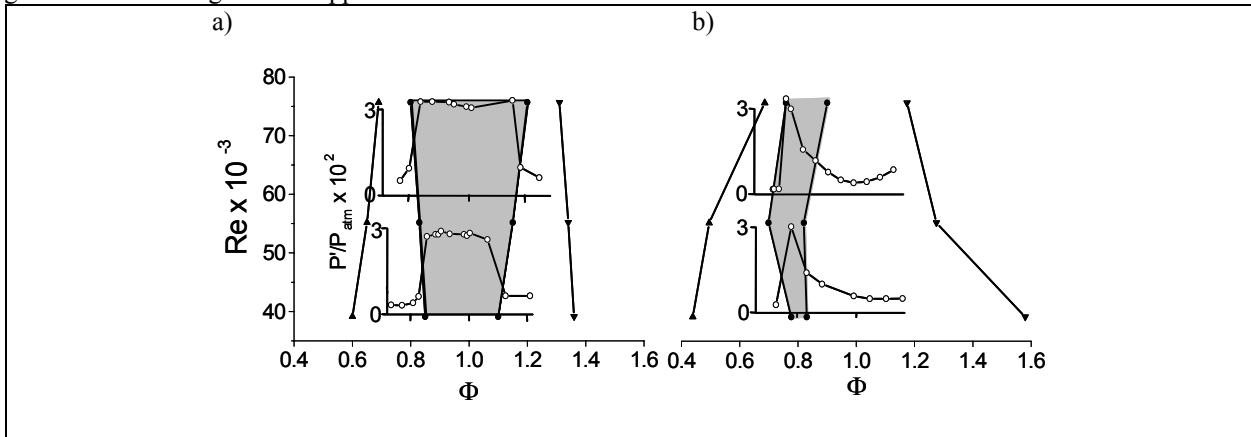

Figure 5: Flammability and stability limits a) methane-air, b) ethylene-air ▲ – Lean limit, ▼ – Rich limit, unstable region is shaded. ○ – Rms pressure amplitudes superimposed for Re = 39,500 and 55,400

The high-amplitude rms pressure fluctuations for methane were near symmetric about stoichiometry at the two Reynolds numbers shown and for interim values. In contrast, ethylene gave rise to a maximum close to an equivalence ratio of 0.8 and a minimum at stoichiometry, after which a steady increase was again apparent towards the rich flammability limit as a consequence of the strengthening partially premixed flame at the duct exit, particularly at high Reynolds numbers. The reason for the minimum in amplitude close to stoichiometry for the ethylene flames is explained by the corresponding spectra of the pressure fluctuations, figure 6, that indicate the co-existence of dominant frequencies based on the upstream and overall lengths of the duct. The excitation of upstream modes was expected from the photographs that showed ethylene flames stabilised close to the expansion step so that even relatively small oscillations were sufficient to move the flame upstream.
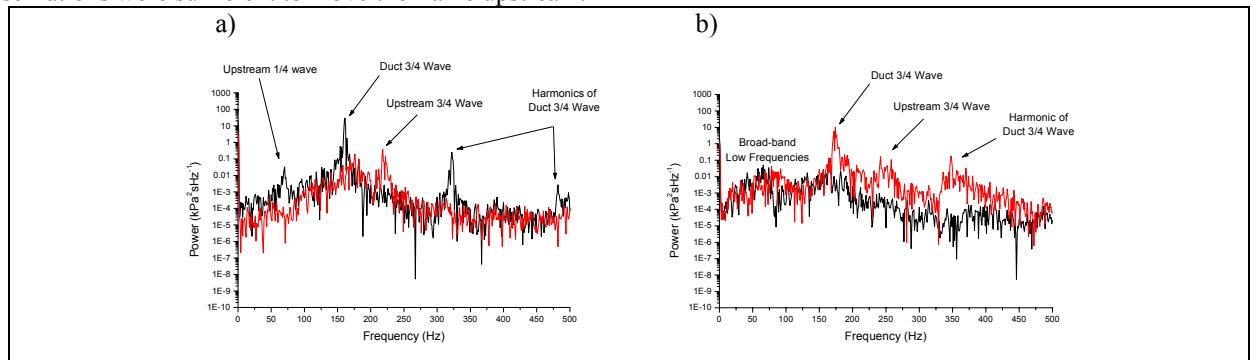

Figure 6: Power spectra of pressure fluctuations. Ethylene: red line. Methane: black line.
a) Re = 60,000, ϕ = 1.0, b) Re = 74000, ϕ = 0.7

Thus, the spectra for ethylene and methane flames at stoichiometry had a peak at around 165 Hz corresponding to the dominant ¾ wave of the entire duct, and that for ethylene had an additional peak at 220 Hz corresponding to the upstream ¾ wave. The boundary conditions for the upstream ¾ wave and that of the entire duct are incompatible, the former requiring a pressure node at the expansion plane and the latter a pressure antinode, so that the competing upstream frequency limited amplitudes with ethylene.

Control

Attempts to control the oscillations involved passive and active methods; the former with imposed acoustic oscillations at discrete frequencies or the addition of small amounts of fuel in the region of highest strain-rate as to improve stabilisation and the latter only with imposed oscillations. Pressure signals of Emiris and Whitelaw (2003) are shown in Figure 7 when the methane-air mixture was at an equivalence ratio of unity and passive forcing and added fuel each contributed to reductions in amplitude, the latter because of a reduction in the tendency to extinction and the related low-frequency modulation of the acoustic signal.
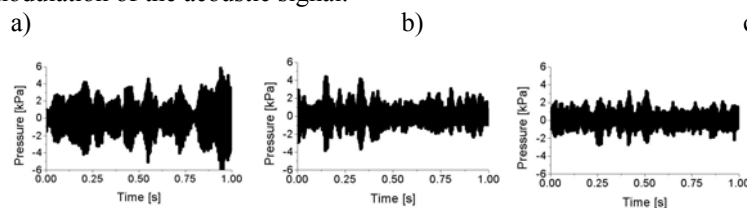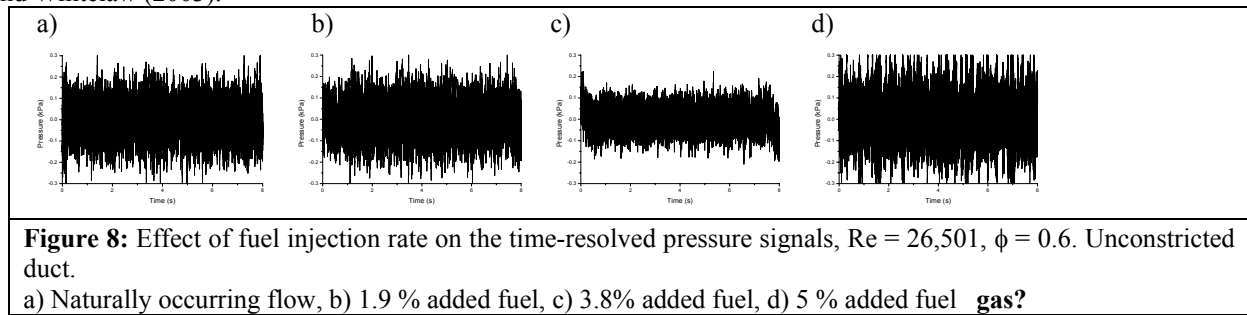

Figure 7: Effect of forcing and fuel injection on the time-resolved pressure signals, Re= 71,000 and ϕ = 1.0. Unconstricted duct.
a) Naturally-occurring flow, b) forcing at 380 Hz and input power of 51 W and c) 3%-added fuel and forcing at 380 Hz and input power of 51 W.

The measurements of figure 8, however, show the sensitivity of signal amplitude to fuel injection rate near the lean extinction limit and the relatively low Reynolds number of 26,501. It is apparent that 1.9 % fuel injection had almost no effect, 3.8% caused a 65 % reduction in amplitude, and 5 % increased the amplitude by 32 %. It is clear that there was a very narrow range of operation in which fuel injection had a positive effect on stability and this is to be expected and more so at higher Reynolds numbers. The position of the injectors is also important, as noted by Emiris and Whitelaw (2003).

Figure 8: Effect of fuel injection rate on the time-resolved pressure signals, Re = 26,501, ϕ = 0.6. Unconstricted duct.
a) Naturally occurring flow, b) 1.9 % added fuel, c) 3.8% added fuel, d) 5 % added fuel   **gas?**

It is evident that the addition of small quantities of fuel can have beneficial effects within limited ranges that may depend on equivalence ratio, Reynolds number and gas. Also, the stabilising effect of added fuel has been shown to be less necessary with the faster flame speed of ethylene, as evident in the lower levels of low frequency noise in the spectra of figure 9, but extinction and relight remained, together with its modulation effects, and the development and appraisal of the method continues.

Passive and active control with imposed acoustic oscillations were successful in reducing the amplitude of methane-air mixtures, and it was apparent that oscillations imposed at a frequency of 400 Hz, close to the second harmonic of the duct ¾ wave, led to the greatest reduction in amplitude, from 4 to just under 2 kPa, and that those imposed at 200 Hz, the first harmonic of the ¾ wave, had the smallest effect. With active control, the frequency was that of the first harmonic due to its greater amplitude and the ease with which the loop could lock on to the signal. The greatest reduction, from 4 to 3 kPa, occurred with a 90-degree phase shift, while passive control provided a reduction to 3.5 kPa at the same frequency. Constructive interference was evident at 270 degrees, leading to an increase in amplitude from 4 to 5 kPa, and the pattern was again repeated, as the phase was shifted further at 90-degree intervals to 630 degrees. It is likely that drivers of greater power would provide better control and that active control is preferable and more so if the signal is phase locked to harmonics of the natural oscillation frequency, such as that at 400 Hz. It also remains to be determined if the same approach will yield similar results with ethylene and to quantify more rigorously the effects of modulation amplitude.

References
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