Flame Stability in Premixed Sudden Expansion Flows with a Stratified Fuel Distribution

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1 Introduction

Methods for reducing NO_x emissions from gas turbine combustors involve maintaining low temperatures of the products of combustion by the addition of water or steam, staging, or operating with low equivalence ratios of premixed fuel and air. The latter can combine the benefits of low NO_x, compact flames and complete combustion but may involve the inter-related problems of stabilisation, instability and extinction which, in turn, may restrict the operating envelope. Round sudden-expansion flows have been used in several lean-burn gas turbine combustors[1-3]. Emiris and Whitelaw[4] examined the possibility of lowering the lean flammability limit by the injection of small quantities of a rich mixture close to the recirculation zone. Although it was possible to lower the lean limit in a premixed methane-air flame from around 0.74 to 0.7 in a duct with an exit nozzle, this method had the problem of determining a priori the appropriate quantity of fuel to be added, since there was a risk of large amplitudes of oscillation with an excess of injected fuel. The possibility of a stratified flow with a lean/rich annular flow and a richer/leaner core to achieve stable lean combustion is examined here. The study of flame behaviour close to the lean flammability limit by De Zilwa et al.[5] showed that extinction in turbulent premixed flames was not an event, as in laminar flames, but a process comprising a sequence of cycles of extinction and relight during which the flame became increasingly weaker, as observed by Bradley et al.[6] in a swirl-stabilised flame and quantified in opposed jet flames by Sardi and Whitelaw[7]. Swirl is known to assist flame stabilisation[8,9] and De Zilwa et al.[9] reported that in sudden expansion flows, low swirl numbers ($S_w \sim 0.1$) could lead to a modest decrease in the lean flammability limit. Larger values of S_w led to an increase in the flammability limit due to increased local strain rates in the vicinity of the step making the flame more prone to local extinction. Korusoy and Whitelaw[10] observed that pressure oscillations decreased with increasing wall temperature in the vicinity of the step and attributed the effect to a reduced probability of local extinction.

2 Aims

The aim of the current work is to quantify the effects of stratification and wall temperature on the lean flammability limit and combustion oscillations over a range of flow conditions close to global extinction. The equivalence ratio and mass flow rate in the core and annular flows are the main variables and the work examines how the lean combustion limit and oscillations are modified by the addition of swirl, added separately to the core and to the annular flow. The impact of stratification and swirl on NO_x emissions is also considered.

3 Method

The sudden expansion arrangement comprised an upstream duct of internal diameter 50.8 mm joined at a step to a duct of internal diameter 80 mm as shown in Fig. 1. A thin-walled core pipe was located coaxially with the upstream duct and permitted stratification of the flow by providing air-fuel mixtures of different concentrations through the core and the annulus between the core pipe and the upstream duct. Two sizes of core pipe, one of 33 and 35 mm inner and outer diameters, respectively, and the other of 24 and 26 mm, respectively, were used so that the ratio of mass flow in the core and the annulus could be varied while keeping the bulk mean velocities the same. The duct lengths upstream and downstream of the step were 1030 mm to guaranty complete flame confinement. This also ensured that the pressure antinode, of the longitudinal ¾-wave for the whole duct, was

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close to the step. Each core pipe was truncated 220 mm upstream of the step and sharpened to a knife-edge to minimise the wake effect behind the core duct and avert the possibility of flame attachment. The fuel (natural gas with 94% methane) and air supplied to the core flow were premixed in a swirl register, with swirl subsequently removed by a honeycomb. Wire-mesh screens were located immediately downstream of the impinging jets in the annulus to remove large-scale fluctuations and render the flow distribution uniform. The air/fuel mixture was ignited at the duct exit using a blow torch. Vane swirlers in the core comprised three blades, in view of the small diameter, while those in the annular pipe had 12 blades. The swirler in the core pipe was located just upstream of its exit plane, and that in the annulus was located 300 mm upstream of the exit plane. The unevenness in the distribution of the swirled flow caused by the boundary layer on the blade walls was expected to decrease to levels comparable with that due to the boundary layer on the core pipe when the flow reached the plane of the step. Flows rates were metered to a precision of 0.5% (of full scale) with calibrated float-type flow meters (Rotameter-KDG Instruments) with readings corrected for density variation by monitoring the pressure and temperature of the fluid at the flow-meter exit. Pressure oscillations were measured with a transducer (Kistler 6121 with charge amplifier 5007) mounted flush with the inner wall of the upstream duct 70 mm upstream of the step, and the signal transmitted via an interface (National Instruments DAQ BNC-2090 and PCI MIO 16E4 A/D card) to a computer for acquisition by software (LabView). Eight seconds of pressure signal data were acquired at 4096 Hz for each condition and post-processed using custom-written software (FORTRAN) to provide the rms amplitude of fluctuation and the peak amplitude to a resolution of better than 0.1%, and the power spectrum to a resolution of 1 Hz. The repeatability of the amplitudes was between 1 and 5% and that of frequency was of the order of 1 Hz.

4 Results & Discussion

Results obtained show that a rich core flow has a limited influence over the flow adjoining the recirculation zone so that it was not possible to lower the value of the overall lean flammability limit below that for a uniformly premixed flow. Furthermore, an increased fuel concentration at the core led to an increase in the lean flammability limit. The latter is sensitive to the wall temperature immediately downstream of the step so that minimising heat losses from the wall is important to ensure flame stabilisation and to avert large amplitude oscillations. The addition of moderate swirl to the annular flow ($S_w \sim 0.2$), as well as to the core flow ($S_w \sim 0.3$), improved flame stabilisation and led to a reduction in the lean flammability limit due to enhanced mixing between the core and annular flow. However, there was no significant reduction below the overall lean limit obtained in uniformly premixed flows without swirl. Stratified flows experience cycles of extinction and relight over a fairly wide range of equivalence ratios adjoining to the lean flammability limit and, for example, a stoichiometry of the annular flow between 0.55 and 0.65 and a core stoichiometry of 0.79 represents a third of the stable operating range. The oscillations, as in uniformly premixed flows, are dominated by a broad-band low frequency of the order of 10 Hz accompanied by the acoustic ¾-wave frequency of the whole duct, and are not amenable to active control due to the modulation in the amplitude and frequency of the oscillations. The addition of swirl improved flame stabilisation so that the tendency for extinction and relight cycles was reduced and the range of annular stoichiometries associated with the broadband frequency was narrowed to less than a half that without swirl and the rms amplitude of oscillation reduced by up to 30%. However, an excess of swirl led to an increase in rms amplitudes associated with the acoustic ¾-wave frequency and sometimes a discrete frequency of the order of 20 Hz in place of the broadband 10 Hz. Stratification of the flow has adverse consequences for NO_x emissions because of regions of higher temperature than in uniformly premixed flows with the same overall equivalence ratio, and the addition of swirl would enhance mixing between the core and annular flows leading to a reduction in NO_x concentrations. The achieved reduction in NO_x with the addition of swirl is due to a more even distribution of temperature in the flow with swirl than without, and the extent of the reduction will diminish as the difference between the core and annular equivalence ratios is reduced. The addition of swirl improved the flame stability and enhanced mixing so that operation near the lean flammability limits could be improved. A comparison between a stratified flow and swirl in the annular and core flow is shown in Fig. 2. It can be seen that moderate swirl had beneficial effects on the lean limits, while excessive swirl led to increased limits as shown for swirl in the core flow. The frequency spectra near the lean extinction limits with and without swirl are shown in Fig. 3. The broadband frequency of 10 Hz which is associated with extinction and relight cycles, was reduced by up to 20 dB in amplitude. It should also be noted that the frequency was shifted by 3-4 Hz with the addition of swirl. The impact of wall temperature on the magnitude of pressure oscillations is exemplified in Fig. 4. Stratification of flows led to an increase in NO_x emissions due to higher heat release in the reaction zone. Moderate swirl had a positive impact on the NO_x emissions measured at the exit plane of the duct and the enhanced mixing resulted in a reduction of up to 50% in emissions as shown in Fig. 5.

5 Conclusions

Premixed reacting flows in a duct with a sudden expansion and a core flow have been examined with the wall temperature, equivalence ratio of the two flows, velocity ratio and swirl as variables in order to determine their influence on the lean flammability limit and oscillations. It was found that addition of moderate swirl to the annular flow improved flame stabilisation and enhanced mixing between the core and annular flow so that the lean flammability limit was reduced. Larger swirl numbers were not beneficial and led to early extinction induced by large amplitudes of oscillation. Oscillations of high amplitude associated with cycles of extinction and relight and leading to global extinction were observed in flows without swirl over a range of annular equivalence ratios extending away from the lean flammability limit. The addition of swirl reduced this range to well below half that without swirl offering the possibility of operation closer to the lean flammability limit. The frequency of the extinction and relight cycles depended on the velocity past the recirculation zone and on the length of the recirculation region. With the velocity increasing and the recirculation length decreasing with swirl, the mean frequency of the extinction-and-relight cycles increased. Improved flame stabilisation by the addition of swirl also meant that the amplitude of oscillations close to the lean limit was reduced although a slight excess of swirl could result in an increase in amplitude. The amplitude of the broadband low frequency oscillations that hamper active control was reduced except very close to the lean flammability limit. However, some lean flow conditions gave rise to a discrete frequency of the order of 20 Hz, which increased with bulk flow rate and swirl. The addition of swirl enhanced mixing so that reductions of order 50% in NO_x emission per unit mass of fuel burnt were possible. The reductions will, however, be less with smaller differences in equivalence ratio between the core and the annulus.

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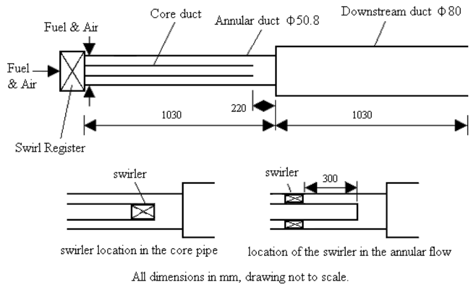

Figure 1. Experimental apparatus

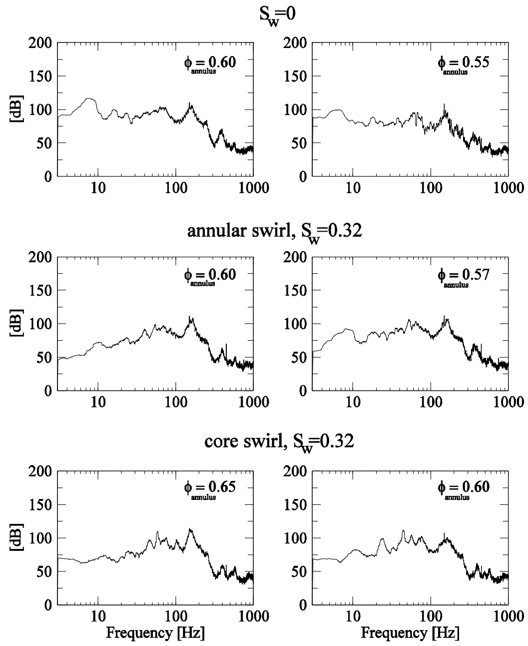

Figure 3. Frequency spectra with and without moderate swirl, 34 mm core pipe, *Re* = 57,000. ϕ_{core} = 0.78.

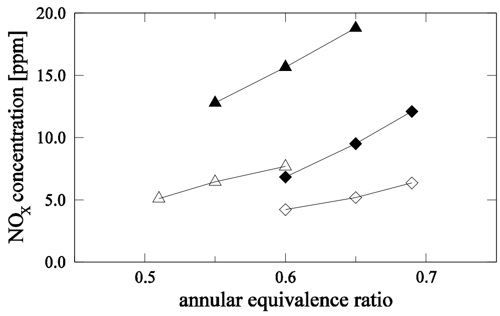

Figure 5. Influence of swirl on NO_x emissions, 34mm core pipe, Re = 57 000, ▲ ϕ_{core} = 0.99, S_w = 0; △ ϕ_{core} = 0.89, S_w = 0.32 in core pipe; ♦ ϕ_{core} = 0.89, S_w = 0; ◊ ϕ_{core} = 0.89, S_w = 0.32 in core pipe.

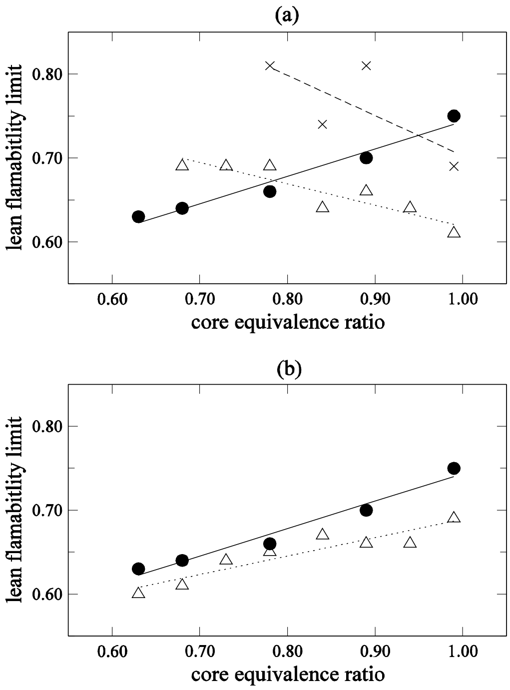

Figure 2. Effect of swirl on the lean flammability limits: *Re* = 57 000, (a) core swirl, △ S_w = 0.32, X S_w = 0.55 and (b) annular swirl △ S_w = 0.14. Filled symbols no swirl.

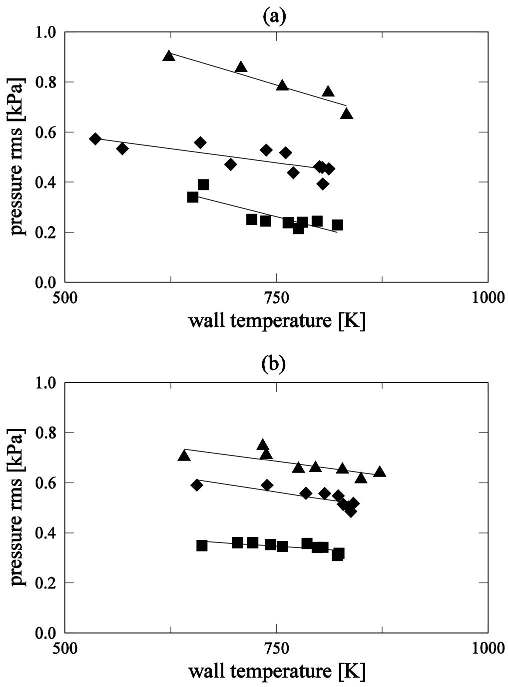

Figure 4. Impact of duct wall temperature on amplitude of oscillations. 34 mm core pipe, Re = 57 000, $\phi_{annular}$ = 0.65, (a) without swirl; (b) with swirl in core pipe (S_w = 0.32) ▲ ϕ_{core}= 0.99; ♦ ϕ_{core}= 0.89; ϕ_{core}= 0.78.