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Proceedings of the Combustion Institute 30 (2005) 1749–1756
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

The response of turbulent premixed flames to normal acoustic excitation

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Abstract

To model the thermo-acoustic excitation of flames in practical combustion systems, it is necessary to know how a turbulent flame front responds to an incident acoustic wave. This will depend partly on the way in which the burning velocity responds to the wave. In this investigation, the response of CH_4/air and CH_4/H_2/air mixtures has been observed in a novel flame stabilisation configuration, in which the premixture of fuel and air is made to decelerate under controlled conditions in a wide-angle diffuser. Control is provided by an annular wall-jet of air and by turbulence generators at the inlet. Ignition from the outlet of the diffuser allows an approximately flat flame to propagate downwards and stabilise at a height that depends on the turbulent burning velocity. When the flow is excited acoustically, the ensemble-averaged height oscillates. The fluctuations in flow velocity and flame height are monitored by phase-locked particle image velocimetry and OH-planar laser induced fluorescence, respectively. The flame stabilised against a lower incident velocity as the acoustic amplitude increased. In addition, at the lowest frequency of 52 Hz, the fluctuations in turbulent burning velocity (as represented by the displacement speed) were out-of-phase with the acoustic velocity. Thus, the rate of displacement of the flame front relative to the flow slowed as the flow accelerated, and so the flame movement was bigger than it would have been if the burning velocity had not responded to the acoustic fluctuation. With an increase in frequency to 119 Hz, the relative flame movement became even larger, although the phase-difference was reduced, so the effect on burning velocity was less dramatic. The addition of hydrogen to the methane, so as to maintain the laminar burning velocity at a lower equivalence ratio, suppressed the response at low amplitude, but at a higher amplitude, the effect was reversed.

Keywords: Premixed; Acoustically excited; Burning velocity

1. Introduction

To suppress NO_x generation in industrial gas turbines fired by natural gas, over the last decade the manufacturers have striven to achieve stable operation under very lean premixed conditions. In this endeavour, it has been necessary to minimise the contribution of the pilot diffusion flame. A major impediment has been the onset of thermo-acoustic excitation, even at equivalence ratios well removed from lean extinction. A promising future strategy is to add a small amount of hydrogen to the fuel to enable even leaner mixtures to be burnt. The effect of this on the thermo-acoustic

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doi:10.1016/j.proci.2004.07.049

instability has to be determined, but there is evidence [1] that the mixtures are more resistant to flame stretch, so it is possible that they are less susceptible to thermo-acoustic excitation.

The influence of fuel properties on the thermo-acoustic phenomenon obviously depends on the mechanisms involved, and these have recently been reviewed [2,3]. One mechanism is the wrinkling of the flame front by the acoustic velocity fluctuations. This is determined not only by the angle of incidence of the acoustic wave, but also by the flame displacement (or turbulent burning) velocity. In treating the flame excitation, some authors (e.g., [4,5]) have assumed that the burning velocity is a constant in space and scales on the time-averaged velocity of the incident flow, and others [6], that it varies along the flame and scales on the pressure fluctuations. The relationship of the turbulent burning velocity to the incident velocity is crucial in these predictions of instability, and so an investigation of the response of flames to plane waves at normal incidence has been undertaken.

The configuration in which the flame was stabilised was a novel one. Premixtures of CH_4/H_2/air formed upstream of a settling chamber were passed through a turbulence-generating mesh and made to decelerate in a conical diffuser in a controlled manner. Ignition from the outlet allowed a flame to propagate upstream in the diffuser and stabilise with only a small degree of mean curvature at a height that depended on the turbulent burning velocity. When the premixture was excited by two speakers on the sides of the settling chamber, the flame oscillated in the diffuser. Phase-locked particle image velocimetry (PIV) and OH-planar laser induced fluorescence (PLIF) measurements allowed the movement of the flame front relative to the incident velocity to be determined.

This paper reports details of the apparatus and the analysis techniques, and presents some results for fuel mixtures with and without hydrogen, excited at various frequencies and amplitudes.

2. Apparatus

The test-section is shown in Fig. 1. The flows of air, CH_4, and H_2 were measured with calibrated mass flowmeters and mixed completely, before being introduced to the mixture supply line upstream of the settling chamber. When leaving this chamber, the flow first passed through a copper gauze flame trap and then a turbulence-generating perforated plate or wire-mesh at the 56 mm diameter outlet. The diffuser, which had a 12.6° half-angle and a height of 150 mm, was manufactured out of quartz so as to allow good UV transmission. Efficient diffusion of the flow was maintained by a high velocity wall-jet of air in a 1 mm annulus [7]. The momentum ratio of this jet to that of the main flow was initially set to give radial uniformity and the theoretical rate of decay in the axial velocity along the axis, as determined by hot-wire measurements without fuel.

However, this momentum ratio was later increased to adjust the shape of the horizontal flame base. Its effect was to increase the rate of decay in velocity and to increase the turbulence intensity throughout the diffuser. The 'flattish' flame base extended over about two-thirds of the diameter of the diffuser, and at the walls, the flame was swept away downstream by the action of the wall-jets. Measurements were therefore concentrated on a region within 15 mm of the axis of the diffuser.

For any given equivalence ratio in the range 0.7–1.0, stable conditions could generally be found within a range of diffuser inlet velocities between 1.5 and 3.5 m/s. Increasing the steady velocity at the inlet drove the flame up the diffuser to a lower velocity region, but this velocity depended on the turbulence and length scale at that particular height. Conversely, increasing the turbulent burning velocity by increasing the equivalence ratio, or adding hydrogen, brought the flame down. Too little momentum in the wall-jet allowed the flame to burn back along the wall-jet interface with the main stream, while too much momentum and entrainment into the wall-jet sucked the flame downwards towards the inlet, and increased its convex curvature to the reactants. The balance was delicate and there was often some visible asymmetry, but flame positions for a given installation of the turbulence generator were accurately reproducible. Acoustic excitation changed the mean flame shape, as discussed below.

Measurements of the velocity field under both steady and acoustically excited conditions were made with 2-D PIV equipment supplied by TSI. An olive oil mist, consisting of 0.6 μm droplets, was introduced into the reactant flow to form the PIV seeding. This seeding was illuminated in a diametral plane by a vertical sheet of light of 532 nm, about 250 μm thick, from a double-pulsed Nd-YAG laser. The interval between the pulses was chosen to be in the range 50–200 μs, depending on the mixture velocity. A 1024 × 1024 frame-straddling camera (PIVCAM 10–30) was positioned at right angles to this plane so as to capture images from a 30 mm square region. These images were analysed by the TSI Insight software in 64 pixel square interrogation regions with 50% overlap to produce velocity vectors in the parts of the image where there was no flame. The flame boundaries were clearly visible due to the evaporation of the droplets at about 600 K.

The fluorescence from OH radicals in the flame was produced with a second laser, a frequency-doubled Nd-YAG pumped dye laser, directed along the same path as that for the PIV. This