Combustion and Flame 160 (2013) 2017–2028

Contents lists available at SciVerse ScienceDirect

Combustion and Flame

journal homepage: www.elsevier.com/locate/combustflame

Flow field measurements of a series of turbulent premixed and stratified methane/air flames

Ruigang Zhou [a,*], Saravanan Balusamy [a], Mark S. Sweeney [a], Robert S. Barlow [b], Simone Hochgreb [a]

[a] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK
[b] Sandia National Laboratories, CA, USA

ARTICLE INFO

Article history:
Received 15 November 2012
Received in revised form 21 February 2013
Accepted 15 April 2013
Available online 10 May 2013

Keywords:
Turbulent combustion
Lean stratified combustion
Co-annular bluff body burner
Laser Doppler anemometry
Particle image velocimetry
Velocity field

ABSTRACT

This paper presents flow field measurements for the turbulent stratified burner introduced in two previous publications in which high resolution scalar measurements were made by Sweeney et al. [1,2] for model validation. The flow fields of the series of premixed and stratified methane/air flames are investigated under turbulent, globally lean conditions ($\phi_g = 0.75$). Velocity data acquired with laser Doppler anemometry (LDA) and particle image velocimetry (PIV) are presented and discussed. Pairwise 2-component LDA measurements provide profiles of axial velocity, radial velocity, tangential velocity and corresponding fluctuating velocities. The LDA measurements of axial and tangential velocities enable the swirl number to be evaluated and the degree of swirl characterized. Power spectral density and autocorrelation functions derived from the LDA data acquired at 10 kHz are optimized to calculate the integral time scales. Flow patterns are obtained using a 2-component PIV system operated at 7 Hz. Velocity profiles and spatial correlations derived from the PIV and LDA measurements are shown to be in very good agreement, thus offering 3D mapping of the velocities. A strong correlation was observed between the shape of the recirculation zones above the central bluff body and the effects of heat release, stoichiometry and swirl. Detailed analyses of the LDA data further demonstrate that the flow behavior changes significantly with the levels of swirl and stratification, which combines the contributions of dilatation, recirculation and swirl. Key turbulence parameters are derived from the total velocity components, combining axial, radial and tangential velocities.

1. Introduction

Fuel-lean, premixed combustion offers low NO_x emissions and high fuel efficiency for many combustion devices [3–5]. Stratified mixtures with non-uniform fuel concentration, can yield better flame stability and ignitability compared with premixed flames under very fuel lean conditions [5,6], and are often intentionally used in practical combustion systems, e.g. stratified charge engines.

Despite widespread use, there is still an incomplete understanding of how stratified flames behave relative to premixed flames at the fundamental level. This has motivated recent research on the effect of stratification on flammability limits [7], flame propagation speed [7,8], flame surface density [9–11], flame brush thickness [9,11,12], scalar dissipation rate [11] and curvature [9–11,13], as well as flame structure [1,2]. The recent papers on the subject by Sweeney et al. [1,2], Seffrin et al. [14] and Kuenne et al. [15] offer a review of the earlier work on the subject, so the present review focuses on the immediately relevant aspects.

A number of recent experimental studies have examined results from novel turbulent stratified burners at practically relevant turbulence levels [10,14,16–18]. Vena et al. [10] examined the effects of equivalence ratio gradients on the topology of flame fronts in a turbulent iso-octane/air V-flame. They observed variations in curvature distributions that were less significant than those reported elsewhere in the methane/air literature. Their main conclusion was that gradient effects on curvature may be limited in flames that are stoichiometric on the mean. Seffrin et al. [14] introduced an axisymmetric concentric-tube burner with a central pilot flame designed to allow the investigation of flames at $Re \sim 10^4$. LDA and PIV were used to characterize the velocity field for a number of operating conditions. The structure of these flames were investigated by Bohm et al. [16] using Rayleigh scattering; the resulting mean and RMS profiles of temperature indicated a higher overall burning rate in the premixed cases relative to the corresponding stratified cases. Examining instantaneous temperature profiles and corresponding OH PLIF images, Bohm et al. concluded that the effect of stratification on temperature profiles is secondary to that of the effect on the three-dimensional flame geometry.

* Corresponding author. Fax: +44 1223765311.
E-mail address: rz242@cam.ac.uk (R. Zhou).

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http://dx.doi.org/10.1016/j.combustflame.2013.04.007

Nomenclature

ϕ_i	equivalence ratio for the inner flow
ϕ_o	equivalence ratio for the outer flow
ϕ_g	global equivalence ratio
U_i	bulk velocity for the inner flow
U_o	bulk velocity in the outer flow
U_{co}	bulk velocity in the co-flow
Re_i	Reynolds number in the inner flow
Re_o	Reynolds number in the outer flow
r	radial position
z	axial position
u	instantaneous axial velocity
v	instantaneous radial velocity
w	instantaneous tangential velocity
$\bar{u}$	mean axial velocity
$\bar{v}$	mean radial velocity
$\bar{w}$	mean tangential velocity
u'	fluctuating axial velocity (RMS)
v'	fluctuating radial velocity (RMS)
w'	fluctuating tangential velocity (RMS)
u_T	large-eddy velocity scale: $u_T = \sqrt{(u'^2 + v'^2 + w'^2)/3}$
$\overline{U}$	total mean velocity
U'	total fluctuating velocity (RMS)
S	swirl number
τ	integral time scale
l	integral length scale
R_{uu}	spatial correlation in the axial direction
Da	Damköhler numbers
Ka	Karlovitz number
s_L	laminar flame speed calculated at $\phi = 0.75$
δ_L	laminar flame thickness calculated at $\phi = 0.75$
l_k	Kolmogorov length scale
τ_k	Kolmogorov time scale
v_k	Kolmogorov velocity scale

Abbreviation

LDA	laser Doppler anemometry
PIV	particle image velocimetry
PSD	power spectral density
ACF	auto correlation function
SR	stratification ratio
SFR	swirl flow ratio

Additionally they found that curvature distributions behaved similarly with stratification to those reported by Anselmo-Filho et al. [9].

The present work investigates the flow fields from methane/air flames in a turbulent swirl burner, described previously in [1,2]. Previous measurements of temperature, major species (CO, H_2, CO_2, H_2O, CH_4, O_2 and N_2), three-dimensional thermal gradients, and curvature of these flames have been acquired using Raman/Rayleigh/CO-LIF combined with simultaneous cross-planar OH-PLIF techniques. The motivation for the present work is to characterize the flow field of the burner, provide a complete velocity database for modelling researchers, and investigate the effect of heat release, stratification and swirl on the flow fields of the burner.

2. Experimental details

An overview of the swirl burner, operating conditions, and experimental details is provided in this section.

2.1. Cambridge/Sandia stratified swirl burner

The slot burner investigated by Anselmo-Filho et al. [9] and the present authors [11] provided detailed information on the effects of stratification in weakly turbulent V-flames as well as a test case suitable for simulation by DNS. It has also attracted interests from RANS modellers [19]. However, the turbulence intensity of the flames surveyed in that burner was much lower than those in practical combustion systems. A burner with substantially higher flow rates, velocities and turbulence levels than the slot burner was designed to investigate the effect of stratification in a more representative flow. The burner was designed to provide flows with a variable degree of swirl; this was to approximate the flow conditions found in many practical applications, and to introduce a greater degree of complexity to the test case. As in practical combustors, the swirl assists flame stabilization, allowing more extreme stratified conditions to be investigated. The swirl burner is referred to as *SwB* throughout the present work.

The swirl burner geometry is detailed in Figs. 1 and 2. The burner is formed from co-annular tubes with a development length exceeding 25 hydraulic diameters to ensure well developed turbulent flow. A ceramic central bluff body is used to stabilize the flame with minimal heat loss. The geometry is described in detail in [1], and full technical drawings are available online [20]. The inner annulus equivalence ratio (ϕ_i) and the outer annulus equivalence ratio (ϕ_o) were independently controlled using mass flow controllers, allowing the stratification ratio ($SR = \phi_i/\phi_o$) to be easily varied. The swirl flow ratio (*SFR*), defined as the ratio of outer annulus flow passing through a swirl plenum relative to the total outer annulus flow, could be independently set, enabling well defined and reproducible swirl levels.

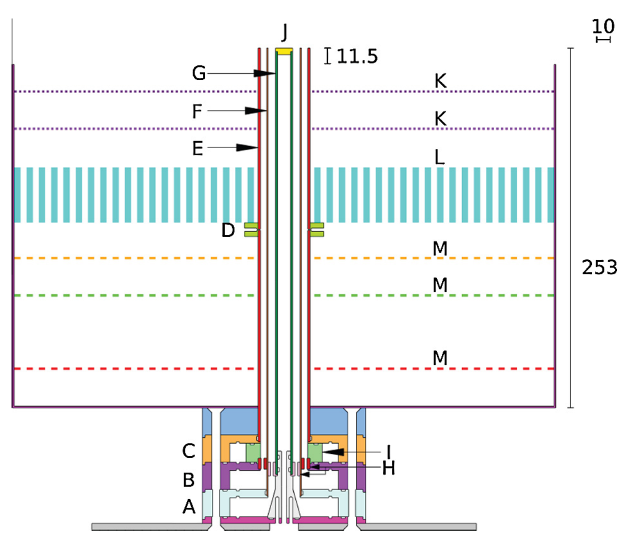

Fig. 1. Cross-section of the stratified swirl burner (*SwB*). (A) Inner annulus plenum; (B) outer annulus axial flow plenum; (C) outer annulus swirl flow plenum; (D) locating collar; (E) outer tube; (F) middle tube; (G) inner tube; (H) flow straighteners; (I) swirl generating collar; (J) ceramic cap; (K) wire mesh; (L) honeycomb section; (M) perforated disk. Flow fittings are omitted for clarity. All dimensions are to scale and in mm.