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A modified piloted burner for stabilizing turbulent flames of inhomogeneous mixtures

Shaun Meares *, Assaad R. Masri

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

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ABSTRACT

A modification of the well-known jet piloted burner is introduced to enable the stabilization of partially premixed flames with varying degrees of inhomogeneity in mixture fraction or equivalence ratio. A second tube is added within the pilot annulus which now surrounds two concentric pipes, one carrying fuel and the other air. The central pipe can also be recessed within the annulus upstream of the burner's exit plane. Two flow configurations are tested: FJ which refers to fuel issuing from the central pipe while air issues from the annulus, and FA where the reverse is true. A key feature of the FJ configuration is that when the central tube is slightly recessed, the fuel partially premixes with air from the annulus inducing inhomogeneity, the extent of which depends on the recession distance.

It is found that flame stability is significantly improved due to this inhomogeneity such that, for intermediate recession distances in the range 50–100 mm, and for the same air/fuel ratio, the blow-off limits for the FJ cases are more than 50% higher than those of the FA counterparts where fuel is injected in the annulus. Detailed stability limits for both the FJ and FA configurations are presented here along with measurements of velocity and mixing fields at the jet exit plane. Rayleigh scattering is used to image mixture fraction in non-reacting jets while measurements of velocity and turbulence fields are made using standard Laser Doppler Velocimetry. It is shown that, at intermediate recession distances, significant differences in the mean and rms fluctuations of the velocity and mixture fraction profiles exist between the FA and FJ cases. An indicator of stratification, extracted from the mixture fraction images at the exit plane of non-reacting jets, confirms that a high degree of inhomogeneity correlates well with improved flame stability.

1. Introduction

While the historical classification of flames into premixed and non-premixed is still useful for academic purposes, it is gradually becoming less relevant in practice with the advent of "mixed mode" combustors that may involve charge stratification, direct injection, exhaust gas recirculation, and low temperature combustion methods. Typical examples of these new generation, low-emission combustors include low temperature diesels (LTD), direct injection stratified charge engines (DISC) and even homogenous charge compression ignition engines (HCCI) [1,2]. Additionally, and with direct injection of sprays, droplets within the flow provide a source of fuel for partial premixing and stratification so that flames crossover a multitude of regimes within the same combustion chamber [3]. It is imperative, therefore, to develop an understanding of, as well as capabilities to compute, flames with inhomogeneities that span a broad range mixture fractions.

Current understanding as well as modeling capabilities of turbulent non-premixed, premixed, as well as homogeneous partially premixed flames have improved significantly, particularly with respect to turbulence-chemistry interactions and associated transient processes such as extinction and re-ignition [4–6]. However, such capabilities are not yet fully tested across the entire mixture fraction space particularly with flames that involve a high degree of inhomogeneity and stratification. The objective of this paper is to introduce a burner that provides a suitable platform for understanding the complexities of such flows and advancing their computations.

It is important at the outset to distinguish between partially premixed flames with inhomogeneous inlet conditions, and homogeneous ones such as those studied by many including the well-known Sandia piloted flames [7,8] where the methane fuel is partially premixed with three volumes of air. The term "inhomogeneity", or "inhomogeneous", as used in this paper refers to the situation where spatial gradients in mixture fraction or equivalence ratio exist so that mixtures exiting the burner may have pockets of reactive fluid adjacent to richer or leaner mixtures. Another point of clarification is with respect to the definition of

* Corresponding author.
E-mail address: shaun.meares@sydney.edu.au (S. Meares).

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Nomenclature

L_r	recession distance of inner tube with respect to jet exit plane
V_A/V_F	volumetric velocity ratio air:fuel
M_A/M_F	mass ratio air:fuel
U_{bo}	bulk velocity at jet exit when blow off occurs
U_J	bulk velocity at jet exit plane
U_{pu}	bulk velocity of pilot (unburnt)
U_c	bulk velocity of coflow
φ_J	bulk equivalence ratio
H_p	heat release of pilot
H_J	potential heat release of jet
D_o	jet diameter
x/D_o	axial location normalized with jet exit diameter
r/D_o	radial location normalized with jet exit diameter
I_{air}	Rayleigh signal of air
I_{CNG}	Rayleigh signal of CNG
I_{data}	Rayleigh signal from measurement location
w_{CNG}	molecular weight of CNG
w_{air}	molecular weight of air
ξ	Mass based mixture fraction of fuel
LDV	Laser Doppler Velocimetry
S_g	stratification parameter
L_K	Kolmogrov length scale
L_I	integral length scale
u	axial velocity
u'	rms of the fluctuating component of axial velocity
Re_t	turbulent Reynolds number
υ	kinematic viscosity

stratification which generally refers to flammable mixtures of varying local gradients such that a multitude of flame speeds may be present. In this paper, the term "stratification" is used somewhat liberally in the context of jet flows where the fluid is still subjected to some shear and turbulent mixing but involves significant inhomogeneities that induce extensive local gradients in mixture fraction. Stratified charge engines exploit the existence of such gradients to enhance flame stability [1,9–11].

Turbulent stratified flames have been studied using a range of burner geometries capable of inducing different levels of stratification [12–22]. Perhaps the most complete investigations are those of Dreizler's group [14,15] and Sweeney et al. [17–19] for which an extensive data base has already been generated. Both groups use two concentric streams where mixtures of different equivalence ratios are injected and the flame is stabilized using either a central pilot [14,15] or a bluff-body [17–19]. The key shortcoming to both configurations is that the extent of stratification is limited by the boundary conditions and the turbulence levels that can be achieved are not sufficiently high to bring the flames to extinction.

Modeling approaches that are now capable of accounting adequately for finite-rate chemistry effects in turbulent premixed and non-premixed flames include laminar flamelets (with a range of advanced multi-variable formulations) [23–26], conditional moment closure [27,28], and probability density function methods [29–32]. All of these approaches are being implemented as subgrid-scale combustion models with Large Eddy Simulation platforms and more details may be found in the recent excellent review of Pope [5]. The immediate outstanding challenge is to demonstrate capabilities to compute finite-rate chemistry effects for a range of flow complexities and for intense levels of stratification. With non-premixed flames, the prediction of increasing local extinction as the flames approach global blow-off has been an important breakthrough [28–30]. In premixed flames, however, the decreasing reactiveness and the transition to broad and distributed reaction zones are proving difficult [32,33]. Attempts to compute the behavior of inhomogeneous partially premixed flames that span the intermediate mixture fraction range (between zero and one) are not extensive but calculations are reported for laminar, stratified flames [34–36] where the mixture fraction gradients are oriented parallel or transverse to gradients in the reaction progress variable. The results clearly show an enhancement in flame speed due to the higher stratification, particularly when the gradients are in transverse rather than parallel modes.

This paper introduces a simple modification to the well-known piloted burner [37,38] to enable the stabilization of partially premixed flames with varying degrees of inhomogeneities. This is achieved by adding another stream to the central pipe such that two concentric tubes (instead of one) are now surrounded by the pilot stream. The central tube, carrying fuel (or air), can slide within the outer tube which carries air (or fuel). The two extreme modes of the burner's operation are obvious: at zero recession, the flames are fully non-premixed; and at sufficiently large recession distances, transition to the fully homogeneous limit occurs. The novelty with the current modification is not in these extremes but rather at intermediate recession distances where the flames become much more stable due to inhomogeneous mixing. Section 2 of the paper shows the improved stability limits while Section 3 reports the mixing fields at the exit plane of non-reacting jets along with the velocity and turbulence fields at this location as well as another downstream location but in a flame. Section 4 introduces an indicator for mixture inhomogeneity and stratification.

2. The burner

The current design involves a simple but innovative modification to the Sydney piloted burner [37,38] which is a well-established platform for modeling turbulent fully non-premixed flames [39–41] as well as homogeneous partially-premixed flames [7,8]. A schematic of the new burner assembly is shown in Fig. 1a. It consists of two concentric tubes referred to hereon as the "inner" or "central" tube or pipe with an inside diameter of D_i = 4 mm (wall thickness of 0.25 mm) and an "outer pipe" or "annulus" with an inside diameter of D_o = 7.5 mm (wall thickness of 0.25 mm). The outer tube is shrouded by the pilot stream which has an inside diameter of D_p = 18 mm and a wall thickness of 0.2 mm. The burner assembly is centered in a wind tunnel with a square cross section of 15 × 15 cm. Fuel can be injected in the inner tube while air flows in the outer tube or vice versa. Figure 1b shows an isometric section of the burner with the recessed inner tube which can slide within the outer tube up to a distance of 500 mm upstream of the exit plane. When both inner and outer tubes are flush with the exit plane, the flame is fully non-premixed while homogeneous mixing occurs when the inner tube is fully recessed. These extremes are well-known so current interest lies in the flame's behavior at intermediate recession distances as described in the remaining sections of this paper.

2.1. Stability limits

Parameters that could affect flame stability are: (i) the bulk jet velocity, U_J (ii) the ratio of bulk air to fuel injected through the