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The response of stratified swirling flames to acoustic forcing: Experiments and comparison to model

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Abstract

The gradient of local equivalence ratio in reacting mixtures significantly affects the flame structure and their corresponding response to acoustic velocity perturbations. We study the effect of acoustic velocity fluctuations on flames created by two co-annular, swirling streams with different equivalence ratios to simulate the effects of pilot-mains split. The flames are stabilized both by a bluff body and by swirl. The flame responses were measured via chemiluminescence as a function of frequency, in the linear perturbation range. A linearized version of the *G*-equation model is employed to describe the flame dynamics, combined with effects of axial and azimuthal velocity perturbations downstream of the swirlers. The model accounts for the phase shift between the main acoustic and swirler vortical perturbations, which propagate at different speeds. The very different flame structures generated by different fuel splits lead to different flame responses. Models based on time delay of vortical disturbances are able to capture the behavior reasonably well for the case of outer fuel enrichment, but offer limited agreement for the case of the inner enriched flame, particularly under higher mean equivalence ratios.

Keywords: Combustion instabilities; Stratified turbulent flame; Flame transfer function; *G*-equation

1. Introduction

Combustion instabilities arise in confined systems from a positive coupling between pressure perturbations and the heat release rate oscillation [1], and have posed significant challenges to the development of advanced gas turbine engines [1–3]. The drive towards lean operation leaves combustion systems more susceptible to acoustic instability and blow off, as the heat release zone is more compact, and more sensitive to air and/or fuel perturbations [4]. A compromise is often made by operating a richer pilot zone surrounded by a leaner mixture. We investigate how such systems respond to acoustic perturbations.

The main drivers of combustion instabilities are fluctuations in acoustic velocity [5,6] and the corresponding changes in equivalence ratio [7–9]. Most previous investigations have been focused on premixed flames, both experimentally and computationally, including laminar [3,5] and turbulent flames [10]. In general the response of the flame is higher at lower frequencies than that at higher frequencies, and the rate of heat release fluctuation (usually as evidenced from chemiluminescence) is linear up to a threshold amplitude,

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beyond which non-linearities arise. The latter are often associated with a significant change in flame shape, by altering the relative phasing of heat release rate and pressure. These non-linearities are usually responsible for determining the end state of the perturbation cycle. The principal difficulty in making predictions of the onset of instabilities lies in establishing an effective model for the flame response as a function of frequency and perturbation amplitude.

Equivalence ratio fluctuations often occur due to imperfect mixing in fuel and air. The combined effects of velocity and equivalence ratio have been investigated in [11]. Scarinci et al. [12] have shown it is possible to decouple the fuel–air mixing process from pressure pulsations in the combustion chamber such that a phased mixing allows the spreading of the time delays of air and fuel fluctuations. Kim and Hochgreb showed experimentally how radial gradients in equivalence ratio simulating pilot-mains distribution can affect flame response [13,14]. These investigations clearly demonstrate the role of phase lag between pressure and equivalence ratio perturbations in determining instabilities.

Acoustic models of combustion systems use network elements characterized by transfer functions [15]. The response of flames to acoustic perturbations in these models is often represented by a flame transfer function (FTF), detailing the gain and phase difference of normalized heat release rate oscillation as function of velocity perturbation. These functions have also been extended into the non-linear range via a flame describing function (FDF) [16–19]. These models use a combination of physically base models and adjustable parameters to describe and understand the physical mechanisms that control the flame dynamic response. Many of the theoretical models have relied on the kinematic *G*-equation, in which the flame surface is presented as an isosurface separating the fresh from burned gases, which moves subject to the action of acoustic waves. Schuller et al. [20] have created a unified framework dealing with conical and V-shaped laminar flames based on this method. Palies et al. [21] extended the model to premixed swirling flames, by suitably accounting for the convected perturbation induced by the swirler. The latter showed that the response of swirling flames is a result of the combined effects of axial and azimuthal velocity components.

In this paper we investigate the influence of an imposed radial split in fuel distribution across the injector on the flame transfer function turbulent flames, at various global inlet conditions. A *G*-equation model adapted to the current conditions is used to understand and explain the response of the flames. We describe the experiment, the model and discuss the comparison and limitations of the latter.

2. Experimental methods

The measurements were performed using an axisymmetric burner shown in Fig. 1. An upstream mixing section consists of two concentric tubes (diameters: 15.80 and 27.75 mm, thickness 1.5 mm) and a centerbody (6.35 mm), which acts as a flame stabilizer. Metered air and fuel mixture is split to flow in two directions: directly to the plenum, or via a graduated ball valve to the siren, to allow control of the amplitude of the acoustic oscillation. The siren consists a stator and a rotating plate, which is controlled by a variable-speed motor (EZ motor Model 55EZB500). Additional fuel is injected about 1000 mm upstream of the combustor chamber entrance into either inner or outer streams to create the desired radial equivalence ratio difference in stratified flames. The volumetric flow rates of both air and fuel are controlled by Alicat mass flow controllers (Air: 0–2000 slpm; Methane: 0–50 slpm & 0–20 slpm; MCR/MC Series, ±0.2% FS accuracy). Two axial swirlers (six vanes of 0.50 mm thickness and 20.0 mm length, angled at 45 degrees to the flow direction, swirl number 0.55) in both the inner and outer tube provide additional flame stability. The outer and inner swirlers end 30.0 and 10.0 mm from the outlet, respectively. The tube ends at a steel plate flush to the combustor inlet. The combustor is an optically accessible fused-silica tube (diameter: 95.0 mm, length: 150.0 mm). The modes are decoupled by appropriate design of the lengths and cross sectional areas of the tubes. All experiments were conducted at ambient temperature and pressure conditions ($T = 20 \pm 2\,^{\circ}$C, $p = 1 \pm 0.02$ bar).

The bulk velocity entering the combustor is 5 m/s. The corresponding Reynolds numbers are approximately 3000 based on this velocity and the hydraulic diameter of each annulus. The stratification ratio (*SR*) is represented by the ratio of

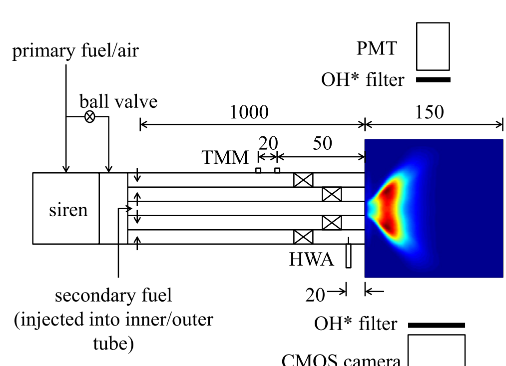

Fig. 1. Schematic of the stratified swirl burner. Dimensions in millimeters, not to scale. Area ratio of inner channel to outer channel, $A_i/A_o = 0.512$.