Combustion and Flame 162 (2015) 1046–1062

Contents lists available at ScienceDirect

Combustion and Flame

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

Response of a swirl-stabilized flame to simultaneous perturbations in equivalence ratio and velocity at high oscillation amplitudes

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ARTICLE INFO

Article history:
Received 8 January 2014
Received in revised form 24 September 2014
Accepted 28 September 2014
Available online 18 November 2014

Keywords:
Gas turbine combustion
Thermoacoustic instability
Flame response saturation
Equivalence ratio fluctuations
Partially premixed combustion
Flame describing function

ABSTRACT

The flame describing function is a valuable tool for the limit-cycle prediction of thermoacoustic instabilities, which are frequently observed in modern gas turbines. In these applications, flames are of lean partially premixed type, and their unsteady response originates from a combination of mechanisms related to perturbations in velocity and equivalence ratio. The interference between these two mechanisms at high forcing amplitudes is the focus of the present study. Well-defined variations of the degree of unmixedness of a practically relevant swirl flame are analyzed to obtain the nonlinear response of the flame to equivalence ratio fluctuations. A lean premixed swirl-stabilized flame is investigated experimentally at atmospheric conditions for a Reynolds number of approximately 35,000. The flow field and the flame dynamics are investigated for perfectly and partially premixed conditions at various frequencies and excitation amplitudes using high-speed particle image velocimetry and OH^*-chemiluminescence imaging. The multi microphone method is applied at different degrees of unmixedness of fuel and air to obtain the nonlinear flame response. By a change in the fuel split between two injection positions the unmixedness is controlled. The nonlinear flame response of the different partially premixed flames and the corresponding premixed flame are analyzed in this study. A decomposition approach is applied to emphasize the trends caused by the contribution of the equivalence ratio perturbations to the flame describing function. Flow field measurements indicate that the flow field dynamics are very similar for the investigated premixed and partially premixed flames. The results of the flame describing function decomposition support the assumption of a superposition of equivalence ratio perturbations and velocity fluctuations effects at low and high forcing amplitudes for most of the investigated frequencies. The decomposition reveals a saturation of the equivalence ratio contribution to the flame response already at small acoustic forcing amplitudes. A conceptual reasoning is presented with the help of a simplified flame model, which explains the observed saturation in the response of partially premixed flames. Increased mixing at high forcing amplitudes is proposed as a new saturation mechanism. Especially at small and intermediate forcing amplitudes as well as higher frequencies, increased turbulence production and changes in the mean flow field lead to an increase of the damping of equivalence ratio fluctuations. An experimentally observed growth of the turbulent shear stresses with increasing acoustic forcing amplitude supports this explanation.

1. Introduction

Lean premixed combustion is a key technology to satisfy stringent regulations for nitrogen oxides (NO_x). The major drawback of this combustion mode is the susceptibility to thermoacoustic coupling [1]. Thermoacoustic heat and pressure oscillations often appear as self-excited instabilities, which can feature limit-cycle amplitudes of up to 5% of the mean pressure level. In gas turbines with combustion chamber pressures of 10–50 bars, thermoacoustic instabilities significantly limit the operation range of the engine [1,2].

The presence of a positive feedback cycle between heat and pressure oscillations is necessary for the development of self-excited thermoacoustic instabilities [3]. If these two oscillations are in phase, heat energy is transferred to the acoustic field and if the amount of energy added by the flame exceeds the acoustic energy dissipation, the system becomes unstable. The self-excitation is caused by the different interaction mechanisms of

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http://dx.doi.org/10.1016/j.combustflame.2014.09.025
0010-2180/

Nomenclature

A_F	flame surface area
a	equivalence ratio oscillation attenuation factor
b	model constant
C	model constant
c	model constant
d	model constant
D_{us}	diameter of the tube upstream of the burner
D_h	hydraulic diameter of burner mixing tube
F	flame describing function
F_u	velocity flame describing function contribution
F_φ	equivalence ratio flame describing function contribution
G_φ	equivalence ratio flame describing function
Δh	heat of reaction per unit mass of mixture
I_{OH}	OH^* chemiluminescence intensity
k	model constant
NO_x	nitrogen oxide
n	model constant
pm	perfectly premixed
ppm	partially premixed
q	heat release rate
$\hat{q}$	Fourier transform of heat release rate
S	swirl number
s_T	turbulent burning velocity
s_L	laminar burning velocity
T	integral shear stress
T_0	integral shear stress of unforced flame
$\bar{u}$	mean axial velocity
u'	acoustic velocity fluctuation
u_{rms}	turbulent velocity fluctuation
$\bar{u}_{bulk}$	bulk velocity in the mixing tube
V	volume
$\mathbf{v}$	velocity vector
$\bar{\mathbf{v}}$	time-averaged velocity
$\mathbf{v}^c$	coherent part of the velocity fluctuations
$\mathbf{v}^s$	stochastic part of the velocity fluctuations
x	axial Cartesian coordinate
y	radial Cartesian coordinate
ε	fuel-split ratio parameter
ω	angular frequency
φ	equivalence ratio
ψ	phase angle
Γ	coherent vorticity
ϑ	temperature
$\hat{\varphi}$	Fourier transform of equivalence ratio
ρ	density
τ_Ω	turbulent shear stress

Subscripts and superscripts

$\hat{}$	Fourier transformed
$\bar{}$	mean quantity
$'$	perturbation in time
lin	linear regime
rms	root mean square
i	pixel/vector index
j	pixel/vector index
c	center of gravity
cc	combustion chamber

the flame. Kinematic effects like wrinkling and the movement of the flame surface are reasons for acoustically induced oscillations of the heat release rate [4–8] especially in laminar flames. There may also be a feedback from the wrinkled flame surface that causes convective perturbations in the upstream flow field. For swirl-stabilized turbulent flames, the major excitation mechanisms can either originate from velocity perturbations or equivalence ratio perturbations (see, e.g., [9,10]). Velocity perturbations are caused by coherent vortices [11] and swirl fluctuations [12–14]. Equivalence ratio perturbation are only relevant for flames that feature mixture inhomogeneities [15].

Swirl fluctuations are generated by an acoustic wave impinging on the swirler. While longitudinal acoustic perturbations travel at the speed of sound, vorticity waves are advected by the mean flow. The heat release rate fluctuations generated by these two mechanisms may thus interfere constructively or destructively. Moreover, the strong shear in the flow field of swirl-stabilized flames facilitates the growth of coherent structures. These are especially important for the pronounced vortex–flame interactions of premixed flames. Schadow and Gutmark [16] interpreted the evolution of coherent flow structures in combustors, which lead to periodic fluctuations in the heat release rate, as shear layer or hydrodynamic instabilities. The vortices are amplified if the shear layers are convectively unstable at the frequency of the thermoacoustic oscillation. The fluctuation of the heat release rate caused by the vortices provides the feedback loop between the flame, the acoustic waves, and the hydrodynamic field [17]. The frequency of the vortex roll-up locks onto the frequency of the acoustic field, which acts as a pacemaker for the coherent structures [18].

Premixed flames (pm) feature velocity perturbations only, because the air and the fuel are perfectly mixed before reaching the flame front. In practical gas turbine burners, air and fuel are usually not perfectly mixed before reaching the flame, and the mixture fraction is therefore not constant. A homogeneous unburned mixture would require a relatively long mixing distance, which cannot be realized for safety reasons due to possible flashback or autoignition. Additionally, flames with a certain degree of mixture fraction inhomogeneity feature a broader operational range. This type of flame is usually referred to as partially premixed (ppm) [19] or, in the application-oriented literature, as technically premixed [20]. Partially premixed flames are affected by equivalence ratio oscillations. Perturbations in the mixture fraction originate from pressure and velocity oscillations at the location of the fuel injection [15,21,22]. These perturbations are advected to the flame, subject to diffusion and dispersion [23,24], and may generate large oscillations in the heat release rate. This is in particular the case for lean combustion, where flame properties such as the burning velocity are strongly susceptible to perturbations in the equivalence ratio [15]. Moreover, strong temporal variations in the mixture fraction may lead to a dynamical displacement of the flame anchoring position, which then results in the generation of unsteady heat release rate [25].

The above mentioned excitation mechanisms and their interaction lead to a frequency dependent response of the flame to flow disturbances commonly referred to as the flame transfer function. The transfer function of the flame can be incorporated into a framework to calculate the linear stability limits of flame–combustor systems [26]. This type of network stability analysis is limited to the linear domain and cannot be used for the prediction of the limit-cycle oscillation amplitude. This remains one of the key-challenges in combustion dynamics related research. The limit-cycle amplitude is determined by an equilibrium of energy addition and removal. Of crucial importance for this equilibrium is the saturation of the flame response at higher acoustic oscillation amplitudes [18]. The nonlinear flame response can be characterized by the flame describing function, which accounts for the dependence