Combustion and Flame 170 (2016) 1–11

Contents lists available at ScienceDirect

Combustion and Flame

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

Onset mechanism of primary acoustic instability in downward-propagating flames

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ARTICLE INFO

Article history:
Received 3 August 2015
Revised 7 May 2016
Accepted 8 May 2016
Available online 26 May 2016

Keywords:
Coupling constant
Coupling mechanism
Growth rate
Laser irradiation
Rayleigh criterion

ABSTRACT

This paper deals with the onset mechanism of primary acoustic instability of downward-propagating flames in a combustion tube. We focus on the effects of a coupling constant, βM, where β and M represent the Zel'dovich and Mach numbers, respectively, and the variation in the flame surface area. To change the coupling constant, various gas compositions for lean ethylene flames diluted with carbon dioxide or nitrogen are used. We obtain a linear relationship between the coupling constant and the average acoustic intensity, and the critical values of the coupling constants are acquired through linear approximation regarding the onset of the primary acoustic instability. Furthermore, we adopt the CO_2 laser irradiation method to alter the shape of the flame front, and experimental results show that the variation in the flame surface area does not always cause spontaneous generation of the primary acoustic instability in initially non-vibrating flames. Furthermore, even in initially vibrating flat flames, the growth rate of the primary acoustic instability is not associated with the increase or decrease in the flame surface area in the present experiments. Finally, we also estimate the effects of acoustic losses on acoustic instability, and experimental results show that larger total acoustic losses tend to suppress acoustic vibration even at the same coupling constant.

1. Introduction

Gas turbine combustors, rocket engines and industrial furnaces are often suffered from thermo-acoustic instability induced by interactions between unsteady heat release and acoustic fluctuations. To protect the industrial applications, the research studies of thermo-acoustic instability have been conducted for a long time in various ways; experiments on a flame propagating in a tube have been the most elementarily adopted.

The experimental observations by Searby [1] constitute a typical example of research in a combustion tube. He reported four distinct regimes of downward-propagating flames in a tube: (1) a curved flame with no acoustic sound just after ignition; (2) a primary acoustic instability with a flat flame surface when the flame has reached the lower half of the tube; (3) a violent secondary acoustic instability with a corrugated flame; and (4) turbulent flame. The secondary acoustic instability is caused by increasing amplitude of the primary acoustic vibration, which is similar to Faraday instability [2–4]. Therefore, the main problem is how to generate the primary acoustic instability because the primary acoustic instability is a key feature of the whole acoustic process. An approach toward resolving this issue has generally been to consider the Rayleigh criterion [5]: an acoustic wave will be amplified if a time integral of the product of pressure and heat release fluctuations is positive over a pressure cycle. Considering this criterion, many previous researchers [6–12] have proposed various mechanisms on primary acoustic instability. We can classify them into two large groups: the direct sensitivity of the reaction rate to acoustic pressure [7,8] (called as "pressure coupling" in the present paper) and the variation in the flame surface area induced by acoustic acceleration [10,11] (called as "acceleration coupling" in the present paper).

Initially, Dunlap [7] theoretically showed that the reaction rate is increased with acoustic pressure fluctuation since the chemical reaction rate is proportional to the density according to Arrhenius law. Also, the variations of gas temperature resulting from adiabatic compression and expansion modulate local heat release rate in phase with acoustic pressure, which causes to develop acoustic vibration. More recently, Clavin et al. [8] treated Dunlap's mechanism and reported that the growth rate of primary acoustic instability is proportional to coupling constant, βM, since Zel'dovich number is a nondimensional measure of the sensitivity of the reaction rate to temperature variations. Therefore, a coupling between the acoustic wave and the heat source easily occurs for large β. However, Clavin's study [8] has limitations which can be applied only for 1-D planar flames. Thus, this analysis is hard to apply to

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http://dx.doi.org/10.1016/j.combustflame.2016.05.008
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Nomenclature

a	amplitude of curved flame
a_f	maximum amplitude of curved flame
A_f	flame surface area
c	speed of sound
C_p	specific heat under constant pressure
E	activation energy
I	sound intensity or acoustic intensity
I	average sound intensity
k	wave number
l_{tip}	flame tip position
L	tube length
P	acoustic pressure
P_o	acoustic pressure at bottom of tube
P_u	acoustic pressure in unburned mixture
q	heat flux
r	tube radius
R	gas constant
S	normalized flame area
S_d	displacement flame velocity
S_L	laminar burning velocity
t	time
T_b	adiabatic flame temperature
T_u	temperature in unburned mixture
u_b	acoustic velocity in burned mixture
u_u	acoustic velocity in unburned mixture
U	flame velocity
w_f	maximum width of curved flame
x	distance from bottom of tube

Greek symbols

α	thermal diffusivity
γ	specific heat ratio
ε	total energy per unit cross-sectional area
λ	wavelength of sound
ν	kinematic viscosity
ξ_u	displacement of unburned mixture
ρ	density
ρ_b	density in burned mixture
ρ_u	density in unburned mixture
τ_a	acoustic time
$1/\tau_{\text{ins}}$	growth rate of acoustic instability
$1/\tau_{\text{loss}}$	total acoustic loss
$1/\tau_{\text{rad}}$	radiative losses
$1/\tau_{\text{wall}}$	wall losses
ω	angular frequency

Dimensionless numbers

β	dimensionless activation energy or Zel'dovich number
M	Mach number ($=S_L/c$)
Pr	Prandtl number ($=\nu/\alpha$)
S	normalized flame surface area
Tr	transfer function defined by Ref. [11]

Subscript

b	burned mixture
f	flame
u	unburned mixture
o	bottom of tube

real combustion experiments since propagating premixed flames in an actual combustor do not take on the planar structure owing to exposure to hydrodynamic instabilities (e.g., D–L instability and gravity effects). Nevertheless, there is ample room to appraise the coupling constant, βM, for fully developed flat flames (the saturated region of acoustic pressure) in the primary acoustic instability.

Another mechanism was proposed by Markstein [10], who suggested that the acoustic pressure modulates a flame shape and can lead to a parametric acoustic instability. An analytical analysis of this mechanism was further performed by Pelcé and Rochwerger [11] in connection with the experiments conducted by Searby [1]. They studied acceleration coupling produced by Darrieus–Landau (D–L) instability and demonstrated that the growth rate of the primary acoustic instability is proportional to $(ak)^2$, where a is an amplitude and k is a wave number of the curved flame. The fundamental principle of this mechanism can be understood as follows: the sufficiently large amplitude of the wrinkled flame caused by D–L instability changes its shape (resulting to surface area change) in phase with pressure fluctuation. The surface area fluctuation induces variation of heat release rate in phase with acoustic pressure, and then the primary acoustic sound is generated [1,2,11]. Their calculation indicates that the maximum growth rate of the acoustic pressure takes place when the flame has reached the lower half of the tube, which is in good agreement with Searby's experimental observations [1]. It should be noted that the flame amplitude by D–L instability changes nonlinearly rather than a stable deformation. However, Pelcé and Rochwerger [11] assumed a constant amplitude in their calculation. Thus, it is required to consider the change of amplitude for the effect of acceleration coupling. However, a and k are very hard to control experimentally because the initial curved flame is intrinsically unstable, even the effect of a and k is significant in the instability mechanism.

To approach this problem, we utilize the novel CO_2 laser-irradiation method to control the shape of the freely propagating flames. Tsuchimoto et al. [13] investigated the oscillating motion of an upward-propagating flame in a tube induced by the CO_2 laser irradiation method, which forms a convex flame surface with the desired dimension toward the unburned mixture. The external laser irradiation preheats an unburned mixture locally in front of a reaction zone, and the flame propagation velocity increases locally. Here, the flame front acquires a strongly curved shape. Park et al. [14] have conducted experiments on downward-propagating flames with CO_2 laser light and have observed a unique deformation of the flame surface (called an "ice-cream flame" in present paper) from a flat flame surface caused by the primary acoustic instability when the flame front is exposed to CO_2 laser light. Since then, Taniyama and Fujita [15] have examined the criteria of a transition from the primary to the secondary acoustic instability induced by a short-term CO_2 laser-irradiation method. In their research [14,15], however, the growth rate of primary acoustic instability depending on variations of flame surface areas was not discussed.

The purpose of this paper is to provide experimental evidence regarding which is the dominant mechanism between pressure coupling and acceleration coupling for the onset of primary acoustic instability of downward-propagating flames in a tube. The both mechanisms theoretically satisfy the Rayleigh criterion; however, experimental verifications are still not enough. Therefore, it is necessary to take into account simultaneously the both mechanisms in the same gas compositions. To achieve that, we apply a systematic control of flame surface area by using laser-irradiation method in the present paper.

The rest of the paper is to investigate the effects of acoustic losses on the primary acoustic instability. Generally, the acoustic losses depend on the geometries of combustion chambers and on the thermal properties of the mixture in the tube. We will present experimental observations of damping effects for the different mixture compositions.