Available online at www.sciencedirect.com
ScienceDirect
Proceedings of the Combustion Institute 000 (2016) 1–8
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Disturbance energy budget of turbulent swirling premixed flame in a cuboid combustor

Kozo Aoki*, Masayasu Shimura, Yoshitsugu Naka, Mamoru Tanahashi

Department of Mechanical and Aerospace Engineering, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152–8550, Japan

Received 4 December 2015; accepted 11 August 2016
Available online xxx

Abstract

In order to clarify combustion oscillation based on the exact disturbance energy budget, three-dimensional direct numerical simulations (DNS) of hydrogen–air turbulent swirling premixed flames are conducted in this study, considering a detailed kinetic mechanism and temperature dependencies of transport and thermal properties. Stoichiometric and lean conditions under two swirl numbers ($S = 0.6$ and 1.2) are investigated. The exact disturbance energy budget is closed to more than 92% for all computational conditions. Investigation of source term contributions reveals that the swirl number affects the order of contribution levels of some sources, while the equivalence ratio influences the fluctuation amplitude of the time derivative value of disturbance energy. It is shown that source terms related to fluctuations of entropy and heat sources are major contributors to disturbance energy growth and decay, respectively. In addition to these major terms, source terms related to non-equilibrium combustion chemistry are also determined to be influential to the time evolution of disturbance energy. The relation between disturbance energy generation and flame characteristics is discussed, based on the time–averaged distributions of some of the abovementioned important sources.

Keywords: Swirling flame; Combustion instability; Exact disturbance energy; Direct numerical simulation; Cuboid combustor

---

1. Introduction

Regulations on pollutant emissions are becoming increasingly strict, requiring combustion techniques with low environmental impacts. Lean premixed combustion is considered to be one of the most effective combustion methods for development of low NOx emission gas turbine combustors. In premixed combustion, it is relatively straightforward to control the homogeneity of the global flame temperature so that NOx formation can be suppressed. However, intensive pressure and flame fluctuations tend to be induced in turbulent lean premixed conditions. This type of combustion instability is called thermoacoustic instability and is considered to be caused, in terms of classical

---

* Corresponding author. Fax: +81 357342505.
E-mail address: aoki.k.aj@m.titech.ac.jp (K. Aoki).

http://dx.doi.org/10.1016/j.proci.2016.08.033
1540-7489 © 2016 by The Combustion Institute. Published by Elsevier Inc.

acoustic energy conservation, by a coupling between pressure and heat release rate fluctuations. This mechanism was first stated by Rayleigh [1], and the following inequality is used as a necessary condition for thermoacoustic instability to occur,

$$\int_{\Omega} p'\omega'_T d\boldsymbol{x} > L, \tag{1}$$

where p' and ω'_T represent pressure and heat release rate fluctuations, respectively, while Ω and L denote combustor volume and acoustic energy loss, respectively. As mentioned earlier, the above criterion is derived from the classical acoustic energy equation in which the correlation term of pressure and heat release rate fluctuations is a source term. Therefore, pressure fluctuation will increase if the left–hand side of the above criterion exceeds the total acoustic energy loss.

Although the Rayleigh criterion has been widely used, even in recent studies concerning combustion instability [2–6], its applicability to turbulent combustion fields is still questionable. Nicoud and Poinsot [7] reviewed the derivation procedure of the Rayleigh criterion and clarified the conditions where it is applicable. Morfey [8] and Myers [9] extended the classical acoustic energy to non-uniform flow fields in order to include the effect of mean-flow. On the other hand, Chu [10] introduced an extended energy concept referred to as the fluctuation energy, which characterizes the intensity of overall disturbances in a flow field, and suggested an alternative stability criterion for disturbance growth. A more generalized energy concept, which is applicable to the general flow field without chemical non-equilibrium, is suggested by Myers [11], and is referred to as the exact disturbance energy. In the disturbance energy equation, several types of energy sources generated through a flame are transferred to various modes of disturbances including acoustic disturbance. It should be noted that these extensions in energy concepts introduce the distinctive evolution of the disturbance energy, which differs from that of the acoustic disturbance.

Recently, Myers' exact energy corollary was reviewed and extended by Giauque and Brear [12,13] so as to include the influence of chemical non-equilibrium. Complete budget closure of the disturbance energy was demonstrated by Giauque et al. [12] by using two-dimensional (2–D) direct numerical simulations (DNS) of an oscillating laminar flame with single-step chemistry. Brear et al. [13] also applied the exact disturbance energy corollary to 2–D slot flames and investigated sound production based on the far–field flux of exact disturbance energy. However, these studies only focus on simple 2–D laminar cases, despite applicability of the exact disturbance energy corollary to any turbulent combustion fields.

In this study, DNSs of a turbulent swirling premixed flame in a cuboid combustor are conducted considering a detailed kinetic mechanism of H_2–air mixture, in order to investigate the exact disturbance energy budget and the critical sources for thermoacoustic instability. The numerical setup and results of the present DNSs are provided in Section 2. In Section 3, the budget closure of the exact disturbance energy is demonstrated and important source terms are identified. The effects of the swirl number and the equivalence ratio on disturbance energy evolution are investigated, based on time–averaged distributions of important sources. Finally, conclusions are drawn in Section 4.

2. DNS of turbulent swirling premixed flames

2.1. Computational methods and conditions

The computational methods of 3–D DNS are shown in our previous works [14–16], and will be only explained briefly here. In our DNSs, a detailed kinetic mechanism with 12 reactive species and 27 elementary reactions for H_2–air mixture is employed [17–19]. Transport and thermal properties are calculated by CHEMKIN packages [19,20] with modifications for vector and parallel computing. Governing equations are discretized by a 4th order central difference scheme in all directions. A 3rd order Runge–Kutta scheme is used for time advancement. In addition, a point implicit method by the VODE solver [21] is only applied for time integrations of a reaction term in order to reduce computation time. Navier–Stokes characteristic boundary condition (NSCBC) [22,23] is imposed on walls, inlet, and exit boundaries to prevent artificial pressure reflections.

The size of the cuboid combustor is 15 mm in the streamwise direction (L_x) with 10 mm × 10 mm cross section ($L_y \times L_z$). The shape of the inlet is a concentric annulus with 0.6-mm-inner and 2.5-mm-outer diameters (D_{in} and D_{out}). Pressure and temperature of the unburnt mixture are 0.1 MPa and 700 K, respectively. In this study, DNSs are carried out under two swirl numbers ($S = 0.6$ and 1.2) and two equivalence ratio conditions ($\phi = 0.6$ and 1.0) in order to clarify their effects on combustion instability. Hereafter, the computational conditions are referred to as, for instance, "S06E06," where "S" and "E," respectively, indicate swirl number and equivalence ratio. Mean axial velocity (u_{ax}) of inflow mixture is 200 m/s and the inflow Reynolds number (Re_{in}) based on u_{ax} and D_{out} is 6100 for $\phi = 0.6$ and 5486 for $\phi = 1.0$. In order to reproduce the realistic inflow boundary condition, a velocity perturbation, composed of 120 sine waves with different frequencies and lifetimes [24], is superimposed on the base flow. The root-mean-square (rms) of the perturbation is 13.2 m/s and the frequency range goes from 3.159 to 1263 kHz [15]. The mean velocity profiles for each direction at the inlet and the definition of the swirl number can be found in a previous work [14]. The Reynolds

Please cite this article as: K. Aoki et al., Disturbance energy budget of turbulent swirling premixed flame in a cuboid combustor, Proceedings of the Combustion Institute (2016), http://dx.doi.org/10.1016/j.proci.2016.08.033