Combustion and Flame 194 (2018) 322–333

Contents lists available at ScienceDirect

Combustion and Flame

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

Flame instabilities and flame cell dynamics in opposed nonpremixed tubular flames with radiative heat loss

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ARTICLE INFO

Article history:
Received 6 February 2018
Revised 17 March 2018
Accepted 10 May 2018

Keywords:
Diffusive-thermal instability
Oscillatory instability
Radiative heat loss
Nonpremixed tubular flame
Linear stability analysis

ABSTRACT

The flame instabilities and flame cell dynamics of opposed nonpremixed tubular flames near radiation-induced extinction limits are investigated using the linear stability analysis and 2-D detailed numerical simulations with three different initial conditions (IC): the perturbed IC, the C-shaped IC, and the asymmetric IC. From the linear stability analysis and 2-D simulations with the perturbed IC for different Damköhler numbers, *Da*, it is found that the flame response to the initial perturbation near the 1-D radiation-induced extinction limit, $Da_{E,R}$, is divided into four different regimes exhibiting different oscillatory and diffusive-thermal (D-T) instability characteristics. The radiation effects on flame structure are identified by examining the transport budgets of flame cells at the stretch-induced extinction limit, $Da_{E,S}$, and the 2-D radiation-induced extinction limit, $Da_{E,P}$. From 2-D simulations with the C-shaped IC, however, it is found that once the D-T instability occur near $Da_{E,R}$, the number of flame cells remains constant and the flame cell size keeps being reduced with increasing *Da* until global extinction occurs, which indicates that flame cells can survive far beyond $Da_{E,R}$ by reducing their size to compensate for significantly-large radiative heat loss. When a tubular flame with the C-shaped IC is initially located beyond $Da_{E,R}$, two identical edge flames can develop and propagate toward each other, leading to extinction by a head-on collision. However, a rotating flame cell can be observed from a tubular flame with the asymmetric IC because a relatively-weak flame cell is quenched prior to the head-on collision. Finally, the flame instability characteristics of opposed tubular flames with extremely-large radiation intensity are identified; high-stretched tubular flames are also affected by radiative heat loss such that the oscillatory instability occurs even at low *Da* and the D-T instability does for all tubular flames that survive within the combustible regime.

1. Introduction

Flames under microgravity exhibit quite different behaviors from their corresponding flames under normal gravity mainly due to buoyancy-free environments. Therefore, numerous theoretical and experimental studies have been performed to elucidate their characteristics especially near ignition/extinction limits [1–4]. For instance, the ignition, flame spreading, and extinction characteristics of weakly-strained flames in a spacecraft have been extensively investigated because such flame characteristics found under normal gravity cannot be directly used for the fire-safety assessment of a spacecraft [5]. The existence of a steady spherical premixed flame or a flame ball has been verified in microgravity experiments. Moreover, flame balls cannot survive beyond a critical flame radius due to stretch effect and radiative heat loss [5–11].

Diffusion- and/or radiation-induced limit phenomena including cellular flame instability and radiation-induced flame extinction have also been widely investigated because they become prominent in microgravity environments. For a nonpremixed flame under microgravity, its flame thickness usually increases with decreasing stretch rate, and hence, radiative heat loss can significantly reduce flame temperature, leading to an extinction [12]. The characteristics of low-stretched flame extinction by excessive radiative heat loss have been extensively investigated in various conditions [13–21]. In particular, the effects of radiative heat loss on spherical nonpremixed flames under microgravity have been identified through comprehensive experimental measurements of flame radius, temperature, radiation intensity, and soot formation [22,23].

Various flame instabilities of nonpremixed flames have also been reported under microgravity conditions. However, there have been few studies on flame instabilities induced by radiative heat loss because it is not only observed less frequently but also difficult to construct experimental environments. It has been predicted that the oscillatory instability of nonpremixed flames can

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https://doi.org/10.1016/j.combustflame.2018.05.012

occur when fuel Lewis number and/or radiative heat loss are large enough [24–26]. For instance, Sohn et al. [27] numerically investigated nonlinear dynamics of radiation-induced oscillatory instability of nonpremixed flames in a 1-D stagnant mixing layer with unity Lewis number such as three different types of flame evolution near radiation-induced extinction limit: the decaying oscillatory solution, diverging solution to extinction, and stable limit-cycle solution. They demonstrated that oscillatory instability occurs prior to extinction due to radiative heat loss, similar to that in a droplet flame experiment in a space shuttle [28].

Moreover, Nanduri et al. [29] investigated the flame structure and dynamics of nonpremixed counterflow flames with radiative heat loss for which fuel Lewis number is less than unity. They observed three oscillatory flame responses of decaying oscillation, stable limit-cycle, and oscillatory extinction for low-stretched flames through 1-D numerical simulations. From 2-D numerical simulations, they observed various flames including wavy flames, stationary cellular flames, and propagating cellular flames depending on initial conditions and Damköhler number. In short, various flame responses such as oscillatory and cellular behaviors of low-stretched nonpremixed flames have been reported, which is primarily attributed to the Lewis number effect and radiative heat loss. However, detailed investigation on nonlinear evolution of 2-D nonpremixed flame oscillations combined with diffusive-thermal (D-T) instability through the stability analysis have not been conducted near radiation-induced extinction limit when fuel Lewis number is less than unity. Moreover, the flame dynamics under extremely-large radiative heat loss has not been elucidated.

In the present study, therefore, the flame instabilities and flame cell dynamics in opposed nonpremixed tubular flames near radiation-induced extinction limits are elucidated by performing 2-D numerical simulations. The results are compared to those of linear stability analysis to identify the onset of oscillatory and/or D-T instabilities near the radiation-induced extinction limit and to examine their flame features. The dynamics of flame cells beyond the radiation-induced extinction limit and flame characteristics in extremely high radiative intensity environment are also investigated.

2. Problem formulation

2.1. 1-D axisymmetric tubular flames with radiative heat loss

As in our previous study [30], an opposed nonpremixed tubular flow configuration is adopted from experiments by Pitz and coworkers [31–35]. Under simultaneous presence of volumetric heat loss and stretch, nonpremixed tubular flames can exhibit dual extinction states: one induced by large stretch and the other by large heat loss [5,29,36]. Prior to performing 2-D simulations of tubular flames, therefore, we first carry out 1-D numerical simulations to examine the characteristics of their extinction states depending on radiative heat loss. Similar to those in previous studies [27,29,37], radiative heat loss is taken into account as a simple optically-thin radiation model in the energy equation. Then, the governing equations of temperature, fuel, and oxidizer species for the opposed nonpremixed tubular flames with radiative heat loss are given by:

$$\tilde{\rho}\tilde{u}_r \frac{d}{d\tilde{r}}\begin{pmatrix}\tilde{c}_p\tilde{T}\\ \tilde{Y}_F\\ \tilde{Y}_O\end{pmatrix} = \frac{1}{\tilde{r}}\frac{d}{d\tilde{r}}\left(\tilde{r}\frac{d}{d\tilde{r}}\right)\begin{pmatrix}\tilde{\lambda}\tilde{T}\\ \tilde{\rho}\tilde{D}_F\tilde{Y}_F\\ \tilde{\rho}\tilde{D}_O\tilde{Y}_O\end{pmatrix} + \tilde{B}\tilde{Y}_F\tilde{Y}_O e^{-\tilde{E}/\tilde{R}\tilde{T}}\begin{pmatrix}\tilde{Q}\\ -\alpha_F\\ -\alpha_O\end{pmatrix} - 4\tilde{\sigma}\tilde{K}_p\begin{pmatrix}\tilde{T}^4-\tilde{T}_\infty^4\\ 0\\ 0\end{pmatrix}, \quad (1)$$

where $\tilde{T}$, $\tilde{Y}_F$, and $\tilde{Y}_O$ are the dimensional temperature, fuel mass fraction, and oxidizer mass fraction, respectively, with the density, $\tilde{\rho}$, radial velocity, $\tilde{u}_r$, specific heat, $\tilde{c}_p$, thermal conductivity, $\tilde{\lambda}$, fuel diffusivity, $\tilde{D}_F$, oxidizer diffusivity, $\tilde{D}_O$, frequency factor, $\tilde{B}$, activation energy, $\tilde{E}$, universal gas constant, $\tilde{R}$, heat of reaction, $\tilde{Q}$, stoichiometric coefficients, α_F and α_O, the Stefan–Boltzmann constant. $\tilde{\sigma}$, the Planck mean absorption coefficient, $\tilde{K}_p$, and independent variable, $\tilde{r}$, denoting the radial direction. In the present study, we adopt a constant density model to investigate flame instabilities assuming an ideal situation without complex flow generated by density variation or thermal expansion [29,30,38–43]. Therefore, the analytic solution of the radial velocity, $\tilde{u}_r$, is used as in [30,44].

By normalizing the dimensional variables with appropriate reference values, i.e. $r = \tilde{r}/\sqrt{\tilde{\lambda}/\tilde{\rho}\tilde{c}_p\tilde{\kappa}}$, $u_r = \tilde{u}_r/\sqrt{\tilde{\kappa}\tilde{\lambda}/\tilde{\rho}\tilde{c}_p}$, $T = \tilde{T}/\tilde{T}_{\mathrm{ref}}$, $Y_F = \tilde{Y}_F/\tilde{Y}_{F,1}$, and $Y_O = \tilde{Y}_O/\tilde{Y}_{O,2}$, Eq. (1) can be written in non-dimensional form with radiative heat loss:

$$u_r\frac{d}{dr}\begin{pmatrix}T\\ Y_F\\ Y_O\end{pmatrix} = \frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right)\begin{pmatrix}T\\ Y_F/Le_F\\ Y_O/Le_O\end{pmatrix} + DaY_FY_Oe^{-T_a/T}\begin{pmatrix}q\\ -\alpha_F\tilde{Y}_{O,2}\\ -\alpha_O\tilde{Y}_{F,1}\end{pmatrix} - Ra\begin{pmatrix}T^4-T_\infty^4\\ 0\\ 0\end{pmatrix}, \quad (2)$$

where Le_F $(=\tilde{\lambda}/\tilde{\rho}\tilde{c}_p\tilde{D}_F)$ is the fuel Lewis number, Le_O $(=\tilde{\lambda}/\tilde{\rho}\tilde{c}_p\tilde{D}_O)$ is the oxidizer Lewis number, Da $(=\tilde{B}/\tilde{\rho}\tilde{\kappa})$ is the Damköhler number, q $(=\tilde{Y}_{F,1}\tilde{Y}_{O,2}\tilde{Q}/\tilde{c}_p\tilde{T}_{\mathrm{ref}})$ is the heat of reaction, T_a $(=\tilde{E}/\tilde{R}\tilde{T}_{\mathrm{ref}})$ is the activation temperature, and Ra $(=4\tilde{\sigma}\tilde{T}_{\mathrm{ref}}^3\tilde{K}_p/\tilde{\rho}\tilde{c}_p\tilde{\kappa})$ is the radiative heat loss parameter. Note that $\tilde{\kappa}$ is the reference stretch rate and is inversely proportional to Da by definition. Note also that Da $(=\tilde{B}/\tilde{\rho}\tilde{\kappa})$ represents the ratio of the convection time to the collision time of the system and is often called the collision Damköhler number [5]. Therefore, even stretch-induced flame extinction occurs at very large Da rather than $Da < 1$. Ra can be expressed as $Ra = Da \cdot I$, where I $(=4\tilde{\sigma}\tilde{T}_{\mathrm{ref}}^3\tilde{K}_p/\tilde{B}\tilde{c}_p)$ is the radiative intensity that will be used as a key parameter determining the magnitude of radiative heat loss. The corresponding non-dimensional boundary conditions at the two inlets are given by:

$$\begin{cases} T = T_1,\ Y_F = 1,\ Y_O = 0,\ u_r = u_{r,1}, & \text{at}\ \ r = r_1,\\ T = T_2,\ Y_F = 0,\ Y_O = 1,\ u_r = u_{r,2}, & \text{at}\ \ r = r_2. \end{cases} \quad (3)$$

Note that the subscripts 1 and 2 denote the fuel and oxidizer inlets, respectively.

To investigate the flame instabilities of nonpremixed tubular flames affected by radiative heat loss, we specify $q = 1.2$, $T_a = 8$, $Le_F = 0.3$, $Le_O = 1.0$, $\alpha_F\tilde{Y}_{O,2} = 1.0$, $\alpha_O\tilde{Y}_{F,1} = 0.36$, $r_1 = 20$, $r_2 = 100$, $T_1 = T_2 = 0.2$, $u_{r,1} = 1$, and $u_{r,2} = -1$. These values are properly adopted to render the maximum flame temperature, $T_{\max}$, at the stretch-induced extinction Damköhler number, $Da_{E,S}$, to be close to unity. Therefore, if $T_1 = T_2 = 0.2$ is assumed to be room temperature of 300 K, $T \approx 1$ represents approximately 1500 K [30,40]. For more details of the problem formulation, readers are referred to [30].

2.2. 1-D steady solutions

Figure 1 shows the response of the maximum flame temperature, $T_{\max}$, of the axisymmetric tubular flames to Da for four different I and the representative radial profiles of the temperature and mass fractions at two critical Damköhler numbers with $I = 10^{-8}$. The profile of the radial velocity, u_r, adopted for the present study is also shown in the figure. The response curves are obtained by solving the governing equations using the Newton-Raphson method with a simple continuation algorithm [30,41]. It is readily observed from the figure that the nonadiabatic tubular flames have two extinction states similar to nonadiabatic nonpremixed/premixed counterflow flames [5,29,36] and the extent