International Journal of Heat and Mass Transfer 99 (2016) 691–701

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Effects of finite-rate droplet evaporation on the extinction of spherical burner-stabilized diffusion flames

Wang Han [a], Zheng Chen [a,b,*]

[a] SKLTCS, Department of Mechanics and Engineering Science, College of Engineering, Peking University, Beijing 100871, China
[b] Department of Aeronautics and Astronautics, College of Engineering, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 31 March 2016
Accepted 1 April 2016
Available online 26 April 2016

Keywords:
Droplet evaporation
Radiation
Lewis number
Spray diffusion flame
Extinction

ABSTRACT

Multiscale asymptotic analysis is conducted for spherical burner-stabilized spray diffusion flames with finite-rate droplet evaporation and nonunity Lewis number. The radiative heat loss is considered and the effects of radiation on flame extinction are examined. The structure function of the spray diffusion flame is derived, based on which the effects of finite-rate droplet evaporation on flame radius, flame temperature, and kinetic and radiative extinction limits are assessed. The flame is found to be affected by droplet evaporation in two ways: (1) the latent heat absorbed for droplet evaporation reduces the flame temperature; and (2) the decrease in the flame radius results in the decrease in radiative loss and residence time. For a given the mass flow rate, only the conventional kinetic extinction limit at low reaction Damköhler number exists. The extinction Damköhler number increases with the radiation intensity and it is significantly affected by droplet evaporation. It is found that at higher radiation intensity, the spray flame with the lower vaporization Damköhler number is relatively more difficult to be extinguished than the purely gaseous flame. When the reaction intensity is fixed and the mass flow rate varies, there exists two extinction limits: a kinetic extinction limit at a low-flow rate and a radiative extinction limit at a high-flow rate. Steady burning only exists between these two extinction limits. The flammable zone is shown to be greatly affected by droplet evaporation and is very sensitive to Lewis number.

1. Introduction

Spray diffusion flames widely exist in propulsion, heating, and power generation systems. Incomplete combustion due to extinction needs to be prevented in order to achieve high efficiency and low emission. Therefore, a fundamental understanding of the extinction mechanism in the spray diffusion flames is helpful for developing high-performance combustion systems. The practical spray combustion process contains poly-disperse sprays in turbulent flows and thereby it requires massive computational resources to simulate and capture the extinction of spray diffusion flames. However, numerical simulations are usually limited to specific fuels and conditions, and hence the conclusions are lack of generality. To get a general understanding of spray combustion, here we conduct theoretical analysis on a deliberately simplified model of spherical burner-stabilized spray diffusion flame and investigate its extinction behavior.

It is well known that flame extinction occurs when there is no enough chemical heat release to balance heat loss. For diffusion flames, there are two types of extinction: kinetic extinction and radiative extinction [1]. In the literature, the kinetic extinction of gaseous diffusion flames was extensively studied. Liñán [2] first analyzed the structure and extinction of counterflow diffusion flames with unity Lewis number and found that flame extinction occurs at a minimum reaction Damköhler number (*Da*, which is the ratio between characteristic flow time and reaction time), which is referred to as the kinetic extinction limit. The kinetic extinction was also observed in droplet combustion [3] and stagnation flame [4]. Chung and Law [5,6] generalized previous studies to different one-dimensional diffusion flames and examined the influence of nonunity Lewis number. They found that the structure function for all one-dimensional diffusion flames can be converted to the same form as that of Liñán [2] and that Liñán's extinction criteria are applicable for different diffusion flames.

Compared to kinetic extinction, radiative extinction of gaseous diffusion flames only occurs in the presence of radiative heat loss and long residence time (large *Da*). Sohrab et al. [7] first theoretically analyzed a counterflow diffusion flame with radiation by

---

[*] Corresponding author at: Department of Aeronautics and Astronautics, College of Engineering, Peking University, Beijing 100871, China.

E-mail address: cz@pku.edu.cn (Z. Chen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.003
0017-9310/

using activation-energy-asymptotic (AEA) analysis. However, the existence of radiative extinction limit at high Damköhler number was not observed in [7] because the results are not properly rescaled. Radiative extinction limit of gaseous diffusion flame was first identified in simulation by T'ien [8], in theoretical analysis by Chao et al. [9], and in microgravity experiments by Maruta et al. [10], after which many studies were performed (e.g., [11–14]). For a spherical burned-stabilized diffusion flame considered here, its kinetic and radiative extinctions were first studied theoretically by Mills and Matalon [15,16] and then it was investigated experimentally by Yoo et al. [17], numerically and experimentally by Tse et al. [18], and numerically by Tang et al. [19,20]. More recently, Wang and Chao [21] have analyzed the kinetic and radiative extinctions of spherical burner-stabilized gaseous diffusion flames with unity Lewis number using multiscale asymptotic analysis and optically-thin radiation model for radiative heat loss. They found that strong radiation and weak reaction can greatly narrow the flammable region.

Unlike purely gaseous diffusion flames, however, spray diffusion flames receive little attention; and in the literature there are only a few studies on the extinction of spray diffusion flames. Li et al. [22] investigated the structure and extinction of counterflow spray diffusion flames with unity Lewis number. They found that the extinction state of spray diffusion flame is similar to that of purely gaseous diffusion flame. This might be caused by the assumption of unity Lewis number since small deviation of Lewis number from unity can result in significant change in the flame temperature [6,12,23]. Wichman and Yang [24] analyzed a double spray counterflow diffusion flame, in which the unity Lewis number assumption was still retained. Greenberg and coworkers [25–31] systematically examined the effects of droplet evaporation and nonunity Lewis number on the kinetic extinction of counterflow spray diffusion flames. They found that the presence of spray promotes kinetic extinction. However, in these studies [25–31], radiative heat loss was not considered and thereby the radiative extinction limit of spray diffusion flames was not observed. Santoro et al. [32,33] experimentally and numerically investigated the vortex-induced extinction behavior in the counterflow spray diffusion flames. Mikami et al. [34,35] experimentally assessed the effects of mean droplet diameter of poly-disperse water spray on the extinction of a counterflow diffusion flame. Kee and coworkers [36–39] numerically examined the flame-droplet interactions in counterflow diffusion flames. However, in these studies the radiative extinction limit was not investigated either.

To the authors' knowledge, in the literature there is no theoretical analysis on the effects of initial droplet load, finite-rate evaporation, and Lewis number on the kinetic and radiative extinction limits of spherical burner-stabilized spray diffusion flames. Therefore, the objective of this work is to examine the influence of finite-rate droplet evaporation on the kinetic and radiative extinctions of spherical spray diffusion flames with nonunity Lewis number. The emphasis is placed on examining how the flame radius, flame temperature, kinetic and radiative extinction limits, and flammable region are affected by the monodisperse droplet vaporization parameters (initial droplet load and vaporization Damköhler number), Lewis number, and radiative loss intensity.

The paper is organized as follows: the mathematical model and analytical solutions are presented in the following two sections; the behavior of spherical spray diffusion flames are investigated in Section 4; and finally, the conclusions are summarized in Section 5.

2. Mathematical model

We consider a spray diffusion flame which is stabilized by a spherical porous burner. The burner and flame structure are depicted in Fig. 1. The spherical burner-stabilized diffusion flame has been popularly adopted to study the extinction and soot formation in diffusion flames (e.g., [17–20,40–42]). Similar to that of Liu et al. [42] and Wang and Chao [21], the burner consists of a void core region ($0 < \widetilde{r} < \widetilde{r}_i$) in which a stream of fuel flow (containing sufficiently small fuel droplet and fuel vapor at the temperature of $\widetilde{T}_0$) is supplied and a porous region ($\widetilde{r}_i < \widetilde{r} < \widetilde{r}_b$) in which the fuel flow is regulated to be uniform at its exist. The fuel flow is steadily injected into a quiescent oxidizer environment ($\widetilde{r}_b < \widetilde{r} < \infty$) at the temperature of $\widetilde{T}_\infty$. It is assumed that droplet evaporation is negligible until droplets leave the burner surface.

It should be emphasized that the droplets are viewed from a far-field vantage point (i.e., in the dilute spray region and accounting for a small volume fraction) in the present analysis. The interactions among the droplets are negligible and dynamic adjustment to equilibrium with their surroundings is instantaneous. Liquid phase velocity is close to that of their host velocity which refers to gas phase velocity. This simplification was validated and popularly used in previous studies [43–46]. Furthermore, the transport properties are supposed to be determined primarily by the properties of the gaseous species [43,45,46]. This follows from the implicit assumption that the liquid fuel volume fraction φ is sufficiently small, i.e., $\varphi \ll 1$. In general, the volume fraction can be of order $\varphi \sim \widetilde{\rho}_g/\widetilde{\rho}_l$ (in which $\widetilde{\rho}_g$ and $\widetilde{\rho}_l$ are density of gas phase and liquid phase, respectively) [47]. The ratio of gas density to liquid density $\widetilde{\rho}_g/\widetilde{\rho}_l$ found in combustion chamber is a small quantity: $10^{-3} \leqslant \varphi = \widetilde{\rho}_g/\widetilde{\rho}_l \leqslant 10^{-2}$ [47]. Therefore, the sufficient small volume fraction falls into the range of $10^{-3} \leqslant \varphi \leqslant 10^{-2}$. It is noted that for the porous spherical burner, there exists a long tube by which the dilute spray and gas fuel is supplied at a steady rate to the core region and hence the liquid volume fraction is also sufficiently small in the core region. For practical purposes, an upper limit on the diameter of droplets in the spray of about 50–100 μm is imposed [45] such that droplets can successfully traverse through the porous burner and then start to vaporize. Droplet burning after passing through the diffusion flame is shown to be negligible due to the small mass fraction of liquid in the initial fuel feed and thereby it is not considered in the present model. Moreover, we consider the spray diffusion flame in a microgravity environment and thereby the flame and flow field are spherically symmetrical. It is noted that the above assumptions limit the validity of results to only qualitative predictions.

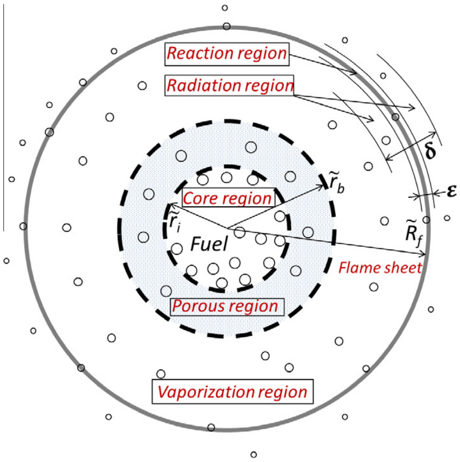

Fig. 1. The schematic diagram of spherical burner-stabilized spray diffusion flame with finite-rate vaporization of droplets (adapted from the figure for purely gaseous diffusion flame in Ref. [21]).