Available online at www.sciencedirect.com

ScienceDirect

Proceedings of the Combustion Institute 35 (2015) 639–646

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

Effect of dilution gas on burning velocity of hydrogen-premixed meso-scale spherical laminar flames

Masaya Nakahara [a,*], Fumiaki Abe [a], Kenichi Tokunaga [a], Atsushi Ishihara [b]

[a] *Department of Mechanical Engineering, Ehime University, Japan*
[b] *Department of Mechanical Engineering, Saitama Institute of Technology, Japan*

Abstract

Aiming to make clear a method for improving combustion of micro/meso-scale flames, effects of dilution gas and characteristic chemical time τ_c on the burning velocity of meso-scale flames were studied experimentally using H_2–O_2–dilution gas mixtures. The meso-scale outwardly propagating spherical laminar flames, in a flame radius r_f range of approximately from 1 to 5 mm, were observed by using sequential schlieren images recorded under appropriate ignition condition. The mixtures at each equivalence ratio ($\phi = 0.5$–1.0) were diluted with Ar, CO_2 or N_2 to set different laminar burning velocities ($S_{L0} = 15$–90 cm/s) at so-called unstretched flames, because τ_c can vary depending on S_{L0}. The radius r_f and the burning velocity S_{Ll} of micro-scale flames were estimated from obtained images. Macro-scale laminar flames with $r_f > 7$ mm were also examined for comparison. It was found that the burning velocities of meso-scale flames for the mixtures diluted with CO_2 at $\phi = 0.5$–1.0 have a tendency to decrease with increasing r_f, and approach those of macro-scale flames, whereas such a trend cannot be seen for the mixtures diluted with Ar as well as N_2 at $\phi = 0.7$–1.0. This shows flame size and Karlovitz number to have optimum values to improve burning velocity. The S_{Ll} at the same r_f; however, tended to meaningfully decrease with the Lewis number *Le* and the Markstein number *Ma*, irrespective of the dilution gas types in addition to ϕ. It also becomes clear that the observed optimal values of each dilution gas are little dependent on τ_c.

Keywords: Premixed meso-scale flame; Burning velocity; Dilution gas; Lewis number; Markstein number

---

1. Introduction

Recently, great attention has been given to combustion at micro/meso scales. With the increasing demands on developments not only of micro combustors for power supplies and heat sources of portable/micro-devices [1–3], but also of high-thermal efficiency and low-emission SI

---

* Corresponding author. Address: 3 Bunkyo-cho, Matsuyama 790-8577, Japan. Fax: +81 89 927 9718.

E-mail address: mnakahara@eng.ehime-u.ac.jp (M. Nakahara).

http://dx.doi.org/10.1016/j.proci.2014.05.050

engines [4–6], which need the assured flame kernel development in a flame initiation stage for reducing misfire, understanding burning velocity characteristics for micro/meso-scale flames is important.

Improving combustion methods at the micro/meso scale is one of the most important issues to further develop small scale combustion devices. The reason is that reducing the size of a combustor would increase heat loss and lead to unstable combustion due to the increasing surface-to-volume ratio and the concept of flame quenching distance. Furthermore, it is difficult to increase combustion intensity by utilizing turbulence in a micro-scale combustor due to the low Reynolds number. One method for improving micro/meso combustors is, therefore, considered in the utilization of hydrogen–oxygen combustion because of high thermal efficiency due to its high flame temperature and the reduction of emission such as NOx and CO_2 [7]. This so-called oxyfuel combustion, however, needs some dilution gas to control the combustion temperature to solve heat-resistance problems of materials for combustors.

Consequently, several studies have made an intensive effort to clarify some characteristics in detail: flame kernel development, relationship of plug diameter and spark gap with minimum ignition energy, combustion characteristics inside a micro channel, micro diffusion flame, and excess enthalpy combustion [1–4,6,8–12]. Recently, there have been theoretical studies in which spherical flame initiation has been examined for fuel–oxygen–He–Ar mixtures paying strong attention to the effect of the Lewis number [13]. In our previous study [14], the influence of fuel types on fundamental properties of burning velocity was examined for meso-scale propagating spherical flames, because the burning velocity is one of the important factors in designing combustors. As a result, it was found that, depending on fuel types, there exists an optimum size and flame stretch to improve burning velocity at which the burning velocity is a maximum value.

However, the effect of dilution gas on the burning velocity characteristics of micro-scale spherical laminar flames still remains unknown. In addition, in the case of diluted mixtures, the characteristic chemical time τ_c is easily expected to be an important factor that affects the laminar burning velocity because variations in dilution rate in the mixture can change burning velocity leading to variations in τ_c.

This study is performed to experimentally investigate the effects of both factors, which are dilution gas and τ_c, on burning velocity characteristics of meso-scale outwardly propagating spherical laminar flames in the range of flame radius r_f approximately from 1 to 5 mm, by using hydrogen–oxygen–dilution gas mixtures, where argon and carbon dioxide in addition to nitrogen are adopted as dilution gas. The values of τ_c achieved will be varied, due to using mixtures whose laminar burning velocity S_{L0} are fixed at 15–90 cm/s controlled by dilution rate at each equivalence ratio ($\phi = 0.5$–1.0).

In order to quantitatively examine the flame radius and the burning velocity of a meso-scale flame, developing flame fronts in a constant volume vessel are recorded by using sequential schlieren photography. The effects of dilution gas types, the Lewis number, the Markstein number and the τ_c on the obtained relationships of flame radius and flame stretch with the burning velocity characteristics are examined. This paper also focuses on assessment for the presence of optimum values of flame size and Karlovitz number to improve burning velocity.

2. Experimental method

2.1. Mixtures and apparatus

Hydrogen (H_2) mixtures used in this study are listed in Table 1. The mixtures with different equivalence ratios ($\phi = 0.5$–1.0) were prepared while maintaining the so-called laminar burning velocity S_{L0} at approximately 15–90 cm/s, by adding dilution gas to H_2–oxygen (O_2) mixtures, where Argon (Ar) and carbon dioxide (CO_2) in addition to nitrogen (N_2) were adopted as a dilution gas. Here, Ar, which has similar diffusivity to N_2, is expected to improve thermal efficiency because of its high specific-heat ratio [7], and CO_2 is an important gas in oxyfuel combustion [15] and has smaller diffusivity than N_2. Due to adopting mixtures having a different S_{L0} at the same ϕ, the effects of characteristic chemical time ($\tau_c = \eta_0/S_{L0}$) as well as dilution gas on burning velocity of meso-scale outwardly propagating spherical laminar flames can be examined, where η_0 is the preheat zone thickness ($=a_0/S_{L0}$) and a_0 the thermal diffusivity. In Table 1, *Le* is the Lewis number ($=a_0/D_d$), D_d the diffusion coefficient of deficient reactant, $D_D/D_{D,N2}$ the ratio of the diffusion coefficient of each dilution gas in the mixture to that of N_2 at the mixture having the same S_{L0} and ϕ, v the kinematic viscosity, and T_p the adiabatic combustion temperature in equilibrium at the constant volume. Here S_{L0} was measured from the pressure history in the chamber in the early stages of combustion where the pressure rises from 0.01 to 0.02 MPa, with uncertainty less than 4% [8,16,17].

The combustion chamber, the same chamber that was used in our previous studies [14,16,17], is a near-spherical vessel with an equivalent inner diameter of about 100 mm, and enough space for meso-scale flames, as shown in Fig. 1. It is equipped with four transparent windows of 85 mm diameter at four rectangular sides, and