Combustion and Flame 172 (2016) 173–182

Contents lists available at ScienceDirect

Combustion and Flame

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

High-temperature, high-pressure burning velocities of expanding turbulent premixed flames and their comparison with Bunsen-type flames

L.J. Jiang, S.S. Shy*, W.Y. Li, H.M. Huang, M.T. Nguyen

Department of Mechanical Engineering, National Central University, Jhong-li District, Tao-yuan City, Taiwan

ARTICLE INFO

Article history:
Received 1 June 2016
Revised 30 June 2016
Accepted 16 July 2016

Keywords:
Turbulent burning velocity
High pressure
High temperature
Expanding turbulent flames
General correlation

ABSTRACT

This paper reports high-temperature/pressure turbulent burning velocities and their correlation of expanding unity-Lewis-number methane/air turbulent flames, propagating in near-isotropic turbulence in a large dual-chamber, constant-pressure/temperature, fan-stirred 3D cruciform bomb. A novel heating method is used to ensure that the temperature variation in the domain of experimentation is less than 1 °C. Schlieren images of statistically spherical expanding turbulent flames are recorded to evaluate the mean flame radius $\langle R(t)\rangle$ and the observed flame speeds, $\mathrm{d}\langle R\rangle/\mathrm{d}t$ and S_F (the slope of $\langle R(t)\rangle$), where S_F is found to be equal to the average value of $\mathrm{d}\langle R\rangle/\mathrm{d}t$ within $25\,\mathrm{mm} \le \langle R(t)\rangle \le 45\,\mathrm{mm}$. Results show that the normalized turbulent flame speed scales as a turbulent flame Reynolds number $Re_{T,flame}=(u'/S_L)(\langle R\rangle/\delta_L)$ roughly to the one-half power: $({S_L}^b)^{-1}\mathrm{d}\langle R\rangle/\mathrm{d}t \approx ({S_L}^b)^{-1}S_F=0.116{Re_{T,flame}}^{0.54}$ at 300 K and $0.168{Re_{T,flame}}^{0.46}$ at 423 K, where u' is the rms turbulent fluctuating velocity, S_L and ${S_L}^b$ are laminar flame speeds with respect to the unburned and burned gas, and δ_L is the laminar flame thickness. The former at 300 K agrees well with Chaudhuri et al. (2012) [16] except that the present pre-factor of 0.116 and $Re_{T,flame}$ up to 10,000 are respectively 14% and four-fold higher. But the latter at 423 K shows that values of $({S_L}^b)^{-1}\mathrm{d}\langle R\rangle/\mathrm{d}t$ bend down at larger $Re_{T,flame}$. Using the density correction and Bradley's mean progress variable $\langle c\rangle$ converting factor for schlieren spherical flames, the turbulent burning velocity at $\langle c\rangle=0.5$, $S_{T,c=0.5}\approx(\rho_b/\rho_u)S_F(\langle R\rangle_{c=0.1}/\langle R\rangle_{c=0.5})^2$, can be obtained, where the subscripts b and u indicate the burned and unburned gas. All scattering data at different temperatures for spherical flames can be represented by $S_{T,c=0.5}/S_L=2.9[(u'/S_L)(p/p_0)]^{0.38}$, first proposed by Kobayashi for Bunsen flames. Also, these scattering data can be better represented by $(S_{T,c=0.5}-S_L)/u'=0.16Da^{0.39}$ with small variations, where the Damköhler number $Da=(L_I/u')(S_L/\delta_L)$ and L_I is the integral length scale.

1. Introduction

The main driving force behind modern combustion research comes from the further development of high-efficiency and low-emission internal combustion engines such as spark ignition engines for transportation and gas turbine combustors for power generation [1,2]. The associated mode is premixed turbulent combustion that frequently takes place in high temperature (T), high pressure (p), turbulent environment. Extensive studies on the subject of premixed turbulent combustion especially focusing on its primary parameter, the turbulent burning velocity (S_T), have been made in the past few decades (e.g., [3–27] among many others). However, most studies were obtained at atmospheric pressure and room temperature conditions (see Refs. [3–8] and references therein) and some at elevated pressure and room temperature conditions (e.g., [9–21] among others with a rapidly growing amount of data recently) but few at high temperature, high pressure, high turbulent conditions. The latter motivates the present work having two objectives. The first objective is to report a novel heating method that allows us to control the temperature variation in the domain of experimentation to be less than 1 °C for measurements of expanding turbulent premixed flames in a large dual-chamber, constant-elevated-pressure, fan-stirred 3D cruciform bomb. Therefore, S_T measurements are free from the influences of temperature gradients that frequently occur using the conventional surface heating method. The second objective is to obtain data of S_T at various p, T, and turbulence conditions, to find a possible general correlation of these S_T data, and to compare our correlation with previous general correlations of both expanding turbulent spherical flames [e.g., 14,16,17,19] and turbulent Bunsen flames [e.g., 9,22].

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* Corresponding author. Fax: +886 3 427 6157.
E-mail address: sshy@ncu.edu.tw (S.S. Shy).

http://dx.doi.org/10.1016/j.combustflame.2016.07.021
0010-2180/

Nomenclature

A	turbulent flame surface area, mm^2
$\langle c\rangle$, $\bar{c}$	mean progress variable
d$\langle R\rangle$/dt	turbulent flame speed by taking time differentiation on $\langle R(t)\rangle$, m/s
d$\langle \overline{R}\rangle$/d$t$	average d$\langle R\rangle$/dt from 4–5 runs at the same condition, m/s
f	fan frequency, Hz
L_I	integral length scale of turbulence, mm
p	initial pressure of reactants, atm
p_0	atmospheric pressure, atm
R	bomb chamber radius measured from its center, cm
R_{min}	minimum wall confinement radius of the 3D cruciform bomb, mm
$\langle R\rangle$	mean flame radius, mm
$\langle R\rangle_{c=0.1}$	$\langle R\rangle$ at $\langle c\rangle = 0.1$, mm
$\langle R\rangle_{c=0.5}$	$\langle R\rangle$ at $\langle c\rangle = 0.5$, mm
$\langle R(t)\rangle$	mean flame radius, mm
S_F	averaged turbulent flame speed, m/s
S_L	planar laminar flame speed with zero stretch, m/s
$S_L{}^b$	laminar flame speed with respect to the burned gas, m/s
S_T	turbulent burning velocity, m/s
$S_{T,c=0.05}$	S_T at $\langle c\rangle = 0.05$, m/s
$S_{T,c=0.1}$	S_T at $\langle c\rangle = 0.1$, m/s
$S_{T,c=0.5}$	S_T at $\langle c\rangle = 0.5$, m/s
T	reactant temperature, K
T_1, T_2, …, T_7	temperatures measured at various thermocouple positions, °C
T_p	perforated plate heater temperature, °C
T_s	surface heater temperature, °C
t	time, s
u'	r.m.s. turbulent fluctuation velocity, m/s

Greek letters

α	thermal diffusivity, mm^2/s
δ_L	laminar flame thickness, mm
ν	kinematic viscosity, m^2/s
ρ_b	burned gas density, kg/m^3
ρ_u	unburned gas density, kg/m^3
ϕ	equivalence ratio

Subscripts

1, 2,…, 7	numbers of thermocouple positions
b	burned
F	flame
min	minimum
p	perforated plate
s	surface
T	turbulence
u	unburned

Dimensionless numbers

Da	turbulent Damköhler number, $Da = (L_I/u')(S_L/\delta_L)$
Le	Lewis number (ratio of thermal diffusivity to mass diffusivity)
$Re_{T,flame}$	turbulent flame Reynolds number, $Re_{T,flame} = (u'/S_L)(\langle R\rangle/\delta_L)$
$Re_{T,flow}$	turbulent flow Reynolds number, $Re_{T,flow} = u'L_I/\nu$

Seeking a general correlation for S_T has long been recognized as one of the key issues of the study of premixed turbulent combustion, as evidenced by the existing general correlations for S_T in the literature [3,5,9–27]. However, others have questioned its usefulness and suggested that S_T is an experimental dependent variable, depending on such as the geometry and type of the burner used in the study [28]. From the fundamental point of view and under the long-held assumption that S_T should be a meaningful physical parameter like an extension of the concept of the laminar burning velocity, there is still the interest to seek a general correlation or a possible unified scaling description of S_T at least in some simplified laboratory turbulent flows such as those in near-isotropic turbulence and in stabilized Bunsen-type turbulent flows. For such a scaling, it is well-known that the commonly-chosen turbulent and flame parameters are respectively the rms deviation from the mean velocity u' and the integral length scale L_I of turbulence and the laminar burning velocity S_L (i.e. the planar laminar flame speed with zero stretch) and the laminar flame thickness δ_L of flame chemistry.

To date, Bradley and his co-workers at Leeds have long used a fan-stirred bomb to extensively measure S_T of statistically spherical premixed flames propagating in near-isotropic turbulence, of which various general correlations of S_T have been proposed [3,5]. Also see a recent paper by Lawes et al. [23] at Leeds for S_T measurements of iso-octane/air mixtures under high-temperature, high-pressure, high-turbulent-Reynolds-number conditions. As to stabilized Bunsen-type turbulent flames under high-temperature and high-pressure conditions, Kobayashi et al. [9,22] have measured unity-Lewis-number methane/air flames at the equivalence ratio $\phi = 0.9$ and reported a general correlation of the form:

$$S_T/S_L = C\left[\left(u'/S_L\right)(p/p_0)\right]^{0.38} \tag{1}$$

where $p_0 = 1$ atm and the constant $C = 5.04$ and 2.90 when S_T were measured at the mean progress variable $\bar{c} = 0.1$ and 0.5, respectively. Note that the validity of Eq. (1) is to be tested via the present measurements of high-temperature, high-pressure S_T of expanding turbulent methane/air flames ($\phi = 0.9$) at $\bar{c} = 0.1$ and 0.5 propagating in near-isotropic turbulence generated by a dual-chamber, constant-pressure, fan-stirred 3D cruciform bomb with newly-designed heating devices. By comparing the present expanding spherical flames with the previous Bunsen-type flames [9,22], both under high-pressure and high-temperature conditions and using the same methane/air mixtures at $\phi = 0.9$, the sensitivity on the geometry and type of the burner is investigated.

Further, Chaudhuri et al. [16] found that a constant-pressure expanding turbulent premixed flame of methane/air mixtures ($\phi = 0.9$; $Le \approx 1$; room temperature) has the self-similar propagation, where all flames at different u' and p can be represented by a normalized turbulent flame speed

$$\left[\left(1/S_L{}^b\right)d\langle R\rangle/dt\right] = 0.102Re_{T,flame}{}^{0.54}. \tag{2}$$

$S_L{}^b$ is the laminar burning velocity on the burned side before density correction. $\langle R\rangle$ is the average flame radius, commonly defined as $\langle R\rangle = \sqrt{A/\pi}$, where A is the area enclosed by the turbulent flame front tracked from high-speed images. t is time. $Re_{T,flame} = u'\langle R\rangle/\alpha$, where α is the thermal diffusivity ($\approx S_L\delta_L$). It should be noted that the power-law relationship between the turbulent flame speed and the turbulent Reynolds number was initially suggested by Kerstein et al. [29] by assuming that the role of turbulence was to distort the topology of the flame front. Chaudhuri et al. [16] then modified this scaling by fluid properties and turbulence length scales with flame properties and geometric characteristics of the flame, respectively, as shown in Eq. (2). Here we add the subscript "flame" to distinguish it from the commonly-used turbulent flow Reynolds number ($Re_{T,flow} = u'L_I/\nu$), where ν is the kinematic viscosity of reactants [14]. In [14], the effect of $Re_{T,flow}$ on high-pressure S_T of expanding turbulent premixed