Flame Speeds and Self-Similar Propagation of Expanding Premixed Turbulent Flames at High Reynolds Numbers

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1 Abstract

This note presents flame speeds and their scaling on large Reynolds-number expanding turbulent premixed flames that propagate in statistically homogeneous isotropic turbulence. Experiments were carried out in a dual-chamber explosion facility, where a large fan-stirred 3D cruciform burner (inner chamber) was resided in a high-pressure outer chamber. Two different mixtures with different Lewis number (*Le*) are measured, respectively lean methane/air at the equivalence ratio $\phi = 0.9$ with $Le \approx 1$ and lean syngas (35%H2/65%CO)/air at $\phi = 0.5$ with the effective $Le \approx 0.76$. Thus, the effect of *Le* on turbulent flame speeds and self-similar propagation are discussed and compared with a recent finding by Chaudhuri et al. (2012) using unity Lewis number expanding turbulent flames in a much smaller dual-chamber, fan-stirred vessel.

2 Introduction

The turbulent flame speed is generally regarded as an important physical quantity in the field of turbulent combustion [1] that has numerous applications from internal combustion engines as the major driving force behind modern combustion research to the explosion of supernovae [2]. A large volume of literatures concerning the turbulent flame speed, a topic of wide interest, is available, as can be found from reviewing articles [e.g., 1,3,4]. The still on-going challenging goal is to seek a unified scaling description on the turbulent flame speed as a function of some non-dimensional parameters that could quantify the coupling interaction between turbulence and chemistry, at least under some special flow conditions such as those in homogeneous isotropic turbulence. Why homogeneous isotropic turbulence? Because the statistical stationarity (steady-in-the-mean) of flame propagation in an inhomogeneous flow field cannot be assured and the turbulent flame speed is inherently ill-defined. However, no actual flows can satisfy all the conditions of isotropy, and thus the best one can do experimentally is to create a flow field that is nearly statistically homogeneous and isotropic [e.g., 5-6]. Further, most previous studies involved small or modest values of flow turbulent Reynolds number ($Re_{T,flow} = u'L_I/\nu$) [e.g., 3,4,7], where u' is the r.m.s. turbulent fluctuation velocity, L_I is the integral length scale of turbulence, and ν is the kinematic viscosity of reactants. It is not clear whether the results obtained at small or modest $Re_{T,flow}$ [e.g., 3,4,7] can be applicable to real engines at high $Re_{T,flow}$. Hence, this motivates the present work to measure flame speeds and their scaling on large Reynolds-number expanding turbulent premixed flames that propagate in statistically homogeneous isotropic turbulence.

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In 2012, Law and his co-workers found that a constant-pressure, unity Lewis number (*Le*) expanding turbulent premixed flame of methane/air mixtures at the equivalence ratio $\phi = 0.9$ has the self-similar propagation [7]. In it the normalized turbulent flame speed $[(1/S_L^b)\mathrm{d}\langle R\rangle/\mathrm{d}t]$ as a function of the average flame radius $\langle R\rangle$ scales as a flame turbulent Reynolds number, $Re_{T,\text{flame}} = u'\langle R\rangle/D_T < 2{,}500$, to the one-half power. S_L^b is the laminar burning velocity on the burnt side before density correlation, t is time, u' is the r.m.s. turbulent fluctuation velocity, and D_T is the thermal diffusivity. Here we add the subscript "flame" to distinguish it from the commonly-used flow turbulent Reynolds number ($Re_{T,\text{flow}}$). The finding of self-similar propagation of expanding turbulent premixed flames is very interesting [7], because all flame speeds at different pressures (p) varying from 1 atm to 5 atm and different values of u' ranging from 1.34 m/s to 6 m/s can be represented by $[(1/S_L^b)\mathrm{d}\langle R\rangle/\mathrm{d}t] = 0.102Re_{T,\text{flame}}^{0.54}$, showing self-similar flame propagation. But such result was based on a rather small range of the average flame radius $\langle R\rangle$ about 10 mm to 25 mm to avoid the wall confinement effect due to the small dual-chamber, fan-stirred vessel used in Ref. [7], where the corresponding values of $Re_{T,\text{flow}} \approx 350 \sim 7{,}500$ and $Re_{T,\text{flame}} \approx 100 \sim 2{,}500$. Thus, the present study aims to address two important questions: (1) Can the aforesaid self-similar propagation of expanding turbulent premixed flames be valid for high $Re_{T,\text{flame}}$ much greater than 2,500 at much higher $Re_{T,\text{flow}}$ up to 80,000 >> 7,500? Does the above self-similar relationship be valid for $Le < 1$ flames?

3 Method

Figure 1 shows a quarter cut view of a novel dual-chamber explosion facility, consisting of a large inner 3D cruciform-shape burner and a huge outer high-pressure vessel. The inner 3D cruciform burner, when it is viewed from all three directions, was constructed and welded by three perpendicularly-aligned cylindrical pipes, each pipe dividing into two symmetrical pieces. As such, a near-spherical volume of a minimum diameter of about 300 mm can be obtained in the central intersection region among these three cylindrical pipes. Two identical sets of specially-designed fan and perforated plate were equipped at the two ends of the largest horizontal pipe (Fig. 1), where the separated distance between the two perforated plates was 420 mm. When the two fans were counter-rotated at the same frequency varying from 3 ~ 182 Hz, a sizable volume of statistically isotropic

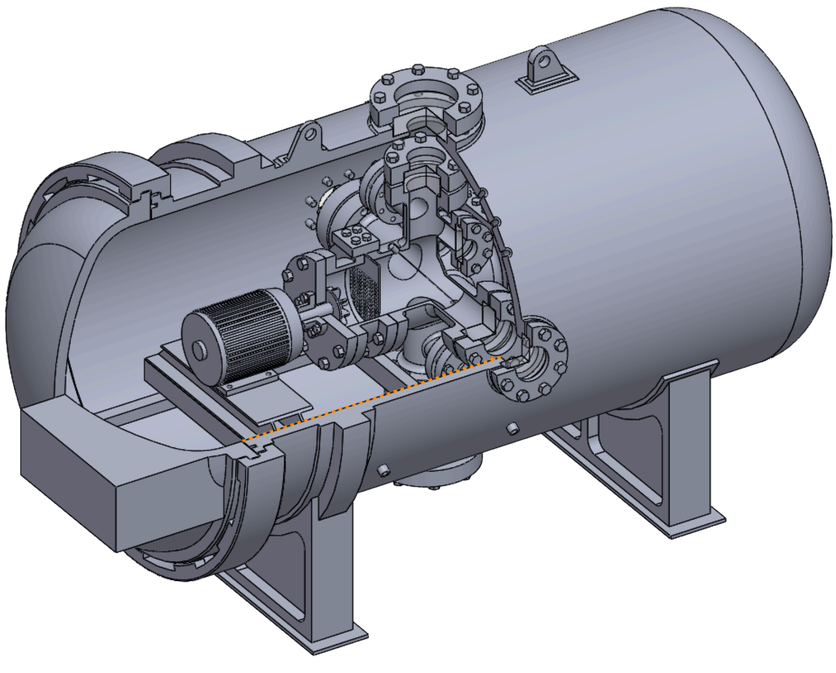

Fig. 1. A novel dual-chamber explosion facility allowing direct imaging and velocity measurements of expanding spherical flames in intense isotropic turbulence at constant elevated pressures, where an inner 3D cruciform burner is resided in an outer high-pressure safety vessel.

turbulence up to 150 x 150 x 150 mm^3 with values of u' up to 8.4 m/s can be generated in the central uniform region. In it the r.m.s. turbulent fluctuation velocities in all three directions are about equal, mean velocities are negligible, and energy spectra have -5/3 slopes. For details, the reader is directed to Ref. [8]. A high-speed Schlieren imaging technique with a view field of 120 x 120 mm^2 was used to measure $\langle R\rangle(t)$ of centrally-ignited, outwardly-propagating spherical premixed turbulent flames using both lean methane/air mixtures at ϕ = 0.9 having $Le \approx 1$ (same as [7]) and lean syngas ($35\%H_2/65\%CO$)/air mixtures at ϕ = 0.5 having an effective $Le_{\mathrm{eff}} \approx 0.76 \ll 1$ [9]. The experiments were performed at pressures of 1, 3, 5 atm and with u' varying from 1.43 m/s to 6 m/s. The domain of experimentation was set at $0.17 \leq \langle R\rangle/R_{\mathrm{min}} \leq 0.33$ to avoid ignition and wall effects, where the minimum wall confinement radius $R_{\mathrm{min}} \approx 150$ mm. Thus, the present maximum $Re_{\mathrm{T,flow}}$ and $Re_{\mathrm{T,flame}}$ can be up to 80,000 and 10,000, much greater than previous studies.

4 Results and Discussion

Figure 2 shows three rows of high-speed Schlieren images for the case of methane (ϕ = 0.9), with different values of p and u' but at roughly same values of $\langle R\rangle$. The fourth column presents instantaneous images of the flame front for nearly same $\langle R\rangle$ values (thin lines), at all conditions of p and u' where turbulent flame speeds are to be discussed below. In addition, the three thick black lines in the fourth column indicates the average values of $\langle R\rangle$, respectively at about 30 mm, 40 mm, and 50 mm, which were obtained by ensemble averaging over all the instantaneous flame fronts. As can be seen from these images in Fig. 2 (see the times), the flame propagates faster with increasing u' and

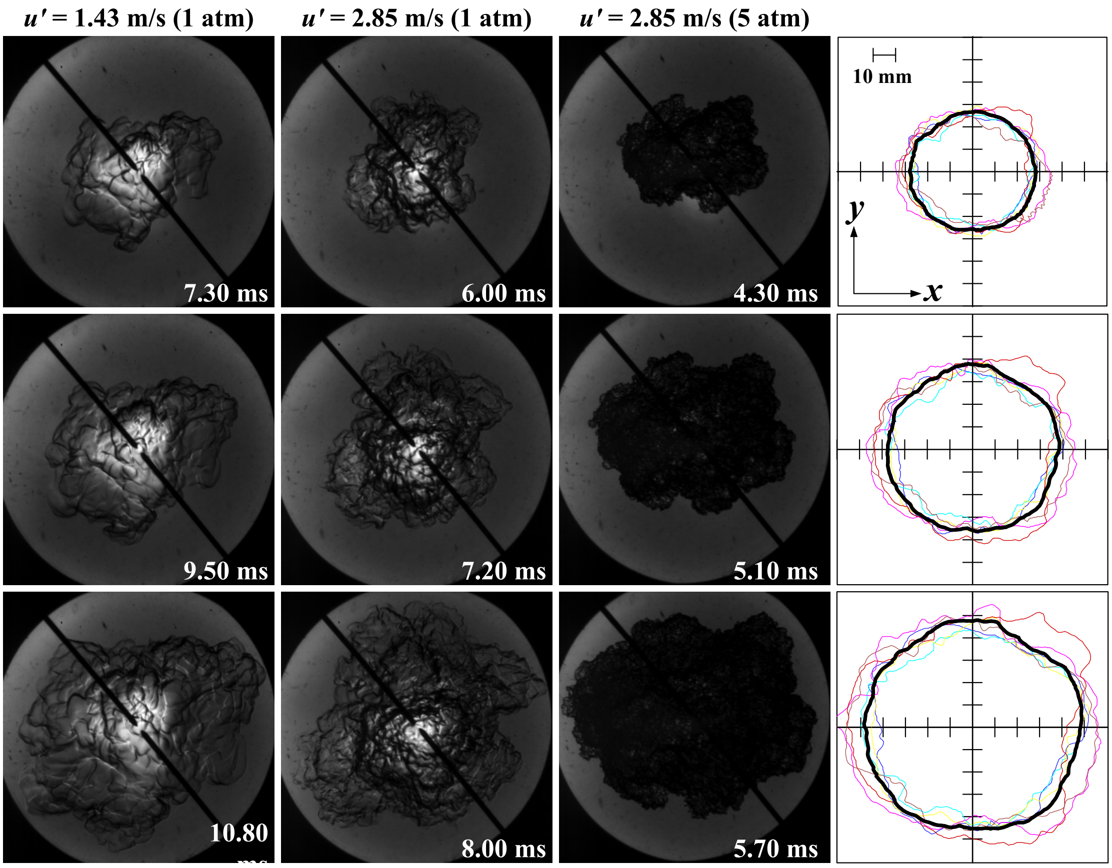

Fig. 2. The case of CH_4/air mixtures with $Le \approx 1$, showing Schlieren images with a view field of 120 mm x 120 mm at different u' and p, but at nearly the same $\langle R\rangle$. Similar to [1], the fourth column shows instantaneous flame fronts (thin lines) for the same $\langle R\rangle$, at various conditions of u' and p. The thick line shows an ensemble avaraging curve over the instantaneous flame fronts.

with increasing p, the flame also propagates faster. The latter is more complicated than just due to the emergence of fine structures (reduction of the thickness of the laminar flamelets with increasing p allowing flame surface wrinkling at progressively smaller scales). Actually, it is mainly influenced by the increase of $Re_{T,flow}$ due to the decrease of ν at elevated pressure [10]. When values of $Re_{T,flow}$ are kept constant, it is found that the average turbulent flame speed decreases similarly as the laminar flame speed with increasing p in minus exponential manners [10].

Figure 3 shows the plot of $(S_L^b)^{-1}d\langle R\rangle/dt$ as a function of $Re_{T,flame} = (u'/S_L)(\langle R\rangle/\delta_L)$, where S_L^b and S_L are respectively the laminar flame speed with respect to the burned gas and unburned gas, δ_L is the laminar flame thickness, and $D_T \sim S_L\delta_L$. Note that $d\langle R\rangle/dt$ was derived from the measured $\langle R\rangle$ *vs. t* data. It is seen that all data of $(S_L^b)^{-1}d\langle R\rangle/dt$ at different instants of all propagation events having different values of p varying from 1 atm to 5 atm and u' varying from 1.43 m/s to 5.60 m/s can merge together and collapse on a $Re_{T,flame}{}^{\alpha}$ curve, where the power law constant $\alpha = 0.54$ is estimated by the least-square fitting over the entire data set. Such a scaling correlation, $(S_L^b)^{-1}d\langle R\rangle/dt = 0.116Re_{T,flame}{}^{0.54}$, reveals that expanding turbulent premixed flames have self-similar propagation, nearly the same as that found by Ref. [7]. For comparison, the previous result of [7], $(S_L^b)^{-1}d\langle R\rangle/dt = 0.102Re_{T,flame}{}^{0.54}$, is also plotted in Fig. 3 (see the inset). Both present and previous results have the same exponent $\alpha = 0.54$ even though the present $Re_{T,flame} \approx 10{,}000$ is four-fold larger than the previous $Re_{T,flame} \approx 2{,}500$, confirming that self-similar propagation of expanding turbulent premixed flames is valid even for $Re_{T,flame}$ up to 10,000. Nevertheless, at given $Re_{T,flame}$, the present normalized turbulent flame speed is about 14% higher than the previous data.

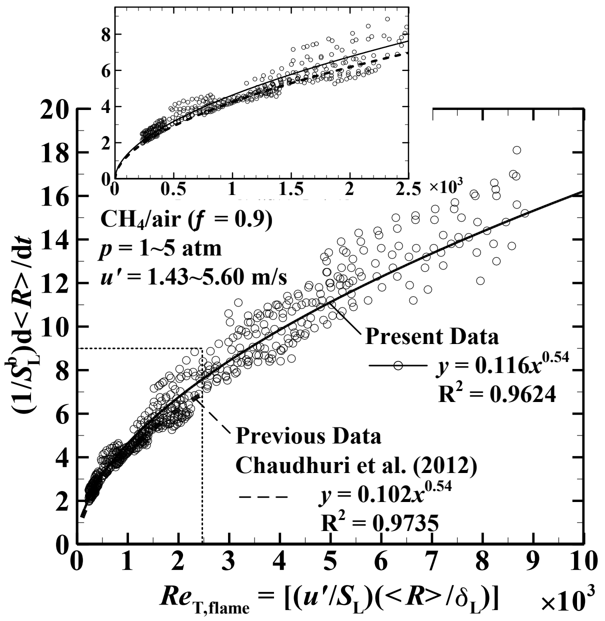

Fig. 3. Comparison between present data (solid line with symbol) and previous data [7] (dash line with $Re_{T,flame} <$ 2,500; see the inset) for the same CH_4/air mixtures at $\phi = 0.9$, showing

Concerning the effect of *Le* on the turbulent flame speed, experiments using lean syngas (35%H_2/65%CO)/air mixtures at $\phi = 0.5$ with $Le_{eff} \approx 0.76 < 1$ are also conducted in order to compare with the aforementioned result using lean methane/air mixtures at $\phi = 0.9$ with $Le \approx 1$. Results are presented in Fig. 4, showing a strong influence of *Le*. It is found that lean syngas flames with $Le \ll 1$ propagate much faster than methane flames with $Le \approx 1$. Specifically the syngas case has the scaling relation, $d\langle R\rangle/dt(S_L^b)^{-1} = 0.190Re_{T,flame}{}^{0.55}$, which is roughly twice higher than that of the methane case. However, the syngas case with $Le \ll 1$ is more scattering than that of the methane case with $Le \approx 1$, where the former has $R^2 = 0.8577$ which is smaller than that of the latter.

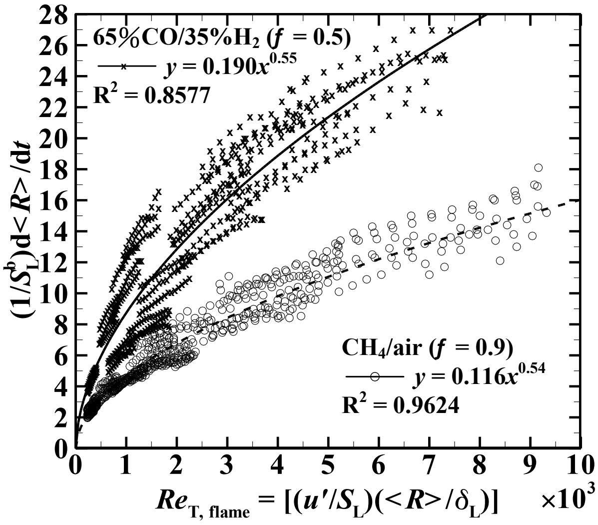

Fig. 4. Lean syngas/air mixtures with $Le_{\mathrm{eff}} = 0.76 << 1$ *vs.* methane/air mixtures with $Le \approx 1$, showing the effect of *Le* on turbulent flame speeds, where values of $[(1/S_L{}^b)\mathrm{d}<R>/\mathrm{d}t]$ in the former are almost twice than that in the latter at any given $Re_{\mathrm{T,flame}}$.

References

[1] Peters N. (2000). Turbulent Combustion. Cambridge University Press (Online ISBN:9780511612701; Book DOI: http://dx.doi.org/10.1017/CBO9780511612701).

[2] Poludnenko AY, Gardiner TA, Oran ES. (2011). Spontaneous transition of turbulent flames to detonations in unconfined media. *Phys. Rev. Lett.* 107(5): 054501.

[3] Driscoll J. (2008). Turbulent premixed combustion: Flamelet structure and its effect on turbulent burning velocities. *Prog. Energy Combust. Sci.* 34(1): 91.

[4] Lipatnikov AN, Chomiak J. (2010). Effects of premixed flames on turbulence and turbulent scalar transport. *Prog. Energy Combust. Sci.* 36(1): 1.

[5] Shy SS, I WK, Lin ML. (2000). A new cruciform burner and its turbulence measurements for premixed turbulent combustion ctudy. *Exp. Thermal Fluid Sci.* 20 (No. 3-4): 105.

[6] Shy SS, Lin WJ, Peng KZ. (2000). High-intensity turbulent premixed combustion: General correlations of turbulent burning velocities in a new cruciform burner", *Proc. Combust. Inst.* 28: 561.

[7] Chaudhuri S, Wu F, Zhu D, Law CK. (2012). Flame speed and self-propagation of expanding turbulent premixed flames. *Phys. Rev. Lett.* 108: 044503-1.

[8] Liu CC, Shy SS, Chen HC, Peng MW. (2011). On interaction of centrally-ignited, outwardly-propagating premixed flames with fully-developed isotropic turbulence at elevated pressure. *Proc. Combust. Inst.* 33: 1293.

[9] Shy SS, Liu CC, Lin JY, Chen LL, Lipatnikov AN, Yang SI. (2015). Correlations of high-pressure lean methane and syngas turbulent burning velocities: Effects of turbulent Reynolds, Damköhler, and Karlovitz numbers. *Proc. Combust. Inst.* 35: 1509.

[10] Liu CC, Shy SS, Peng MW, Chiu CW, Dong YC. (2012). High-pressure burning velocities measurements for centrally-ignited premixed methane/air flames interacting with intense near-isotropic turbulence at constant Reynolds numbers. *Combust. Flame*, 159: 2608.