Fuel Similarity and Turbulent Burning Velocities of Stoichiometric Iso-octane, Lean Hydrogen, and Lean Propane at High Pressure

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1 Introduction

Knowing how fast a premixed turbulent flame can burn or propagate in high-pressure environment plays an important role on the performance of spark ignition (SI) engines and gas turbine combustors, as evidenced by the existing numerous publications in literature (e.g., [1-10] among many others). The focus is on measurements of turbulent flame speeds (S_F) or turbulent burning velocities (S_T) of combustible mixtures at high-pressure [2,3,5,7-9] and high-temperature [1,4,6,10] conditions. Most S_T studies [1-5,7-10] applied gaseous fuels such as methane and syngas, but rare using liquid fuel such as iso-octane [6]. Since iso-octane is the major surrogate component for gasoline [11], understanding of turbulent flame propagation of iso-octane through the two-way interaction between flame kernel and turbulence is important to SI engines. Even a small improvement of fuel efficiency in SI engines will have a significant impact on economy and environment. Hence, the first objective is to measure values of S_F or S_T of stoichiometric iso-octane/air mixture at $T = 423$ K and $p = 1 \sim 5$ atm in a well-controlled near-isotropic turbulent flow field over a wide range of turbulent intensities (u'/S_L), where u' is the rms turbulent fluctuating velocities and S_L is the laminar burning velocity.

The second objective is to seek a better general correlation for S_T that has long been recognized as one of the key issues of the study of premixed turbulent combustion [12]. However, others had doubts on its usefulness and suggested that S_T was an experimental dependent variable, depending on the geometry and the type of the burner used in the study [13]. Under the long-held assumption that S_T should be a meaningful physical parameter just like an extension of the concept of S_L from the fundamental point of view, it is still interesting in seeking a general correlation of S_T. Hence, we aim to find out a possible unified scaling description of S_T at least in some simplified laboratory turbulent flows such as that in near-isotropic turbulence generating by the fan-stirred bomb. For such a scaling, the commonly-chosen turbulent and flame parameters are respectively u' and L_I of turbulence and S_L and δ_L of flame chemistry, of which their combination is the turbulent Damköhler number $Da = (L_I/u')(S_L/\delta_L) = Re_{T,flow}(u'/S_L)^{-2}$, where L_I is the integral length scale of turbulence, δ_L is the laminar flame thickness, $Re_{T,flow} = u'L_I/\nu$, and ν is the kinematic viscosity of reactants [5]. Here we use the subscript "flow" to distinguish it from the turbulent flame Reynolds number $Re_{T,flame} = u'<R>/\alpha$ used in [7], where α is the thermal diffusivity ($\approx S_L\delta_L$) and $<R>$ is the average flame radius. In [5], the effect of $Re_{T,flow}$ on high-pressure S_T of expanding turbulent premixed flames of methane/air mixtures was carefully measured by controlling the product of $u'L_I$ in proportion to the decreasing ν at elevated pressure because $\nu \sim \rho^{-1} \sim p^{-1}$ (constant $Re_{T,flow}$). When $Re_{T,flow}$ can be kept constant, we discovered that values of S_T decrease similarly as S_L with increasing p in minus exponential manners, revealing a global response of burning velocities to pressure [5]. At fixed p, the higher the constant value of $Re_{T,flow}$ is, the higher the value of S_T/S_L. Results of [5] indicated that the commonly-held opinion related with the promotion effect of increasing pressure on S_T fundamentally due to the enhancement of flame instabilities via the thinner flame without any discussion on the influence of $Re_{T,flow}$ elevation at elevated pressure should be reconsidered. Furthermore, all scattering values of S_T/S_L at different constant pressures varying from 1 to 10 atm and at different constant $Re_{T,flow}$ varying from 6,700 to 14,200 [5] can be represented by a general correlation of the form: $(S_T - S_L)/u' = 0.14Da^{0.47} \sim Da^{0.5}$. Similar general correlations scaling as Da to the one-half power had been early proposed by Peters [14] and Shy et al. [15,16] for atmospheric turbulent premixed flames. In this study, measured S_T data of stoichiometric iso-octane/air mixture at T = 423 K and $p = 1 \sim 5$ atm having an effective Lewis number Le = 1.43 will be analyzed by using such general correlation scaling as Da to the one-half power and taking the effect of Lewis number into consideration for the first time. Further, other fuels i.e. hydrogen (ϕ = 0.6) and propane (ϕ = 0.7) are also measured at $p = 1 \sim 5$ atm at room temperature (298 K) to seek a possible unified scaling description of S_T.

2 Experimental Method

The dual-chamber, constant-temperature, constant-pressure, fan-stirred cruciform explosion facility has recently been used to measure turbulent burning velocities of centrally-ignited, outwardly-propagating turbulent premixed flames at high temperature and high pressure conditions using methane as a fuel [10]. The reader is directed to Ref. [10] and references therein for detail treatment on the facility and its associated turbulence properties. In this work, we use the same facility to measure three different fuels i.e. stoichiometric iso-octane, lean hydrogen at ϕ = 0.6, and lean propane at ϕ = 0.7, covering $Le < 1$ and $Le > 1$.

Before a run, we first vacuum the heated (150°C) 3D cruciform burner before injecting appropriate mole fraction of pre-vaporized iso-octane from a separate heated fuel cylinder by means of the partial pressure method. Second, air is filled into the burner to the desired initial pressure. Third, we turn on the two counter-rotating fans at the rotating frequency of 30 Hz to well mix the iso-octane/air mixture for 4 minutes. As these two counter-rotating fan-stirred vortical streams pass through the two heated perforated plates, a uniform temperature distribution in the domain of experimentation can be obtained (please see [10] for details). The present iso-octane fuel is fully vaporized and well-mixed in the heated cruciform burner (the boiling temperature of iso-octane is about 98°C). As to the lean H_2/air and lean propane/air mixtures at 25°C, the procedures are the same except that heating is not applied. A run begins by centrally-igniting the well-mixed reactants using a pair of freely-suspended electrodes of 2 mm diameter with sharp ends, as can be seen from Fig. 1 in the next section. We apply high-speed schlieren imaging to record the time evolution of the average flame radii, where $\langle R\rangle(t) = [A(t)/\pi]^{0.5}$. $A(t)$ is the area enclosed by the turbulent flame front tracked from high-speed images and t is time. The domain of experimentation is set at $0.17 \leq \langle R\rangle/R_{min} \leq 0.30$ to avoid the ignition influence at the early stage of kernel development and the wall effects at the later stage of flame propagation, where the minimum wall confinement radius of the 3D cruciform bomb R_{min} is about 150 mm. Hence, we calculate $d\langle R\rangle(t)/dt$ and S_F or S_T from the raw data of $\langle R\rangle(t)$ in the range of 25 mm $\leq \langle R\rangle \leq$ 45 mm (not shown). $d\langle R\rangle/dt$ is directly taking the time differentiation on $\langle R\rangle(t)$, while S_F is determined as the slope of the best linear-fit of $\langle R\rangle(t)$ within 25 mm $\leq \langle R\rangle \leq$ 45 mm. Within this domain of experimentation, S_F is just the average value of the near-linear (stable) increase data of $d\langle R\rangle/dt$ (see Fig. 4b of [10]).

3 Results and Discussion

Figure 1 shows a typical set of schlieren images for iso-octane/air mixture at ϕ = 1 at 423 K with different p and u' but at the same $<R> \approx$ 20 mm, 30 mm and 40 mm. By comparing the columns 1 and 2 in Fig. 1 having the same u' = 1.4 m/s and T = 423 K, turbulent flame propagates much faster at 5 atm than at 1 atm. The latter takes 8.8 ms to propagate 20 mm (column 1), while the former only takes 2.6 ms to propagate the same distance (column 2), as can be seen from the instant times indicated in Fig. 1. It is intuitive to attribute such increase on the turbulent flame speed to the enhancement of flame instabilities via the thinner flame at higher pressure (5 atm), since the fine scales that are all over the surface of turbulent spherical flames (column 2) are observed. But the actual enhancement mechanism of turbulent flame speed is not mainly due to flame instabilities via the thinner flame at higher pressure. It is the effect of the flow turbulent Reynolds number that plays a much more important role. We know that the kinematic viscosity decreases linearly with pressure ($\nu \sim \rho^{-1} \sim p^{-1}$), where $\nu \approx 2.76 \times 10^{-5}$ m^2/s at 1 atm and $\nu \approx 5.51 \times 10^{-6}$ m^2/s at 5 atm for the iso-octane/air mixture at ϕ = 1 when T = 423 K. Also, $L_I \approx 10.7 f^{0.34}$ (mm) and $u' \approx 0.0462 f$ (m) which were previously measured by extensive LDV and PIV [15,16]. Therefore, the value of $Re_{T,flow} \approx$ 8,864 at 5 atm (column 2) is five-fold greater than that of 1 atm ($Re_{T,flow} \approx$ 1,730; column 1). Further, when $Re_{T,flow}$ can be kept constant

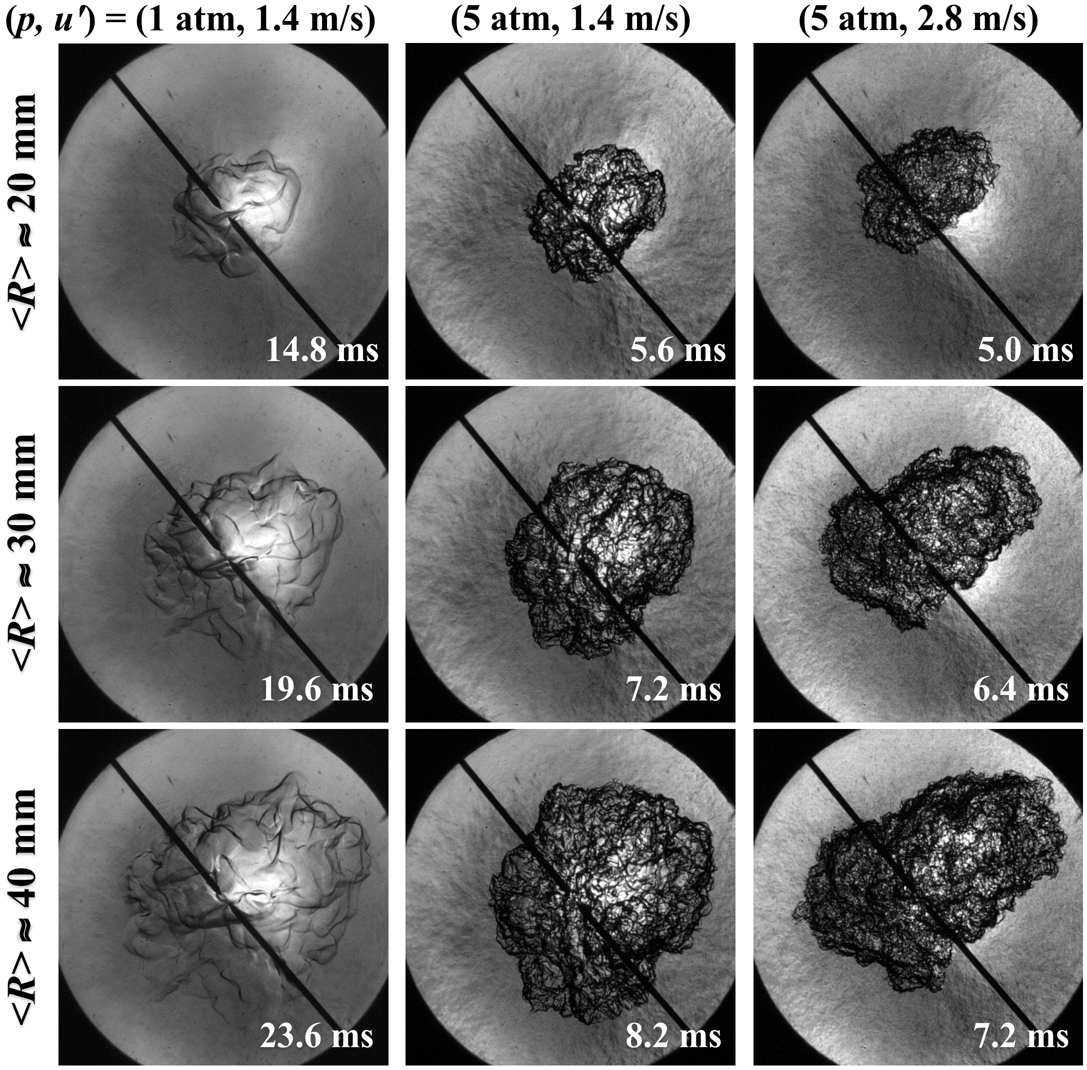

Fig. 1. Schlieren imaging of stoichiometric iso-octant/air premixed flames with Le = 1.43 propagating in isotropic turbulence at two different p and u' but at the same $<R>$. Field of view: 110 x 110 mm^2.

by controlling the product of $u'L_I$ in proportion to the decreasing ν at elevated pressure, it is found that S_T decreases similarly as S_L with increasing p in minus exponential manners, as discovered by Liu et al. [5]. Such discovery can be further appreciated by comparing images at the same p = 5 atm but at different u' (columns 2 & 3), of which u' increases from 1.4 m/s to 2.8 m/s. As seen, the effect of increasing u' and thus $Re_{T,flow}$ at the same 5 atm (columns 2 & 3) plays an important role on the structure of fine scales, where $Re_{T,flow}$ = 21,953 at u' = 2.8 m/s (column 3) is about 2.5 times greater than $Re_{T,flow} \approx$ 8,864 at u' = 1.4 m/s (column 2). This is the main reason why the wrinkled fine scales at u' = 2.8 m/s are much more dense than that at u' = 1.4 m/s, both at the same p = 5 atm having the same thinner laminar flame thickness (see Fig. 1). Turbulent flames propagate faster at the higher value of u' = 2.8 m/s than that at u' = 1.4 m/s. Hence, the enhancement of turbulent flame speed is principally due to the increasing effect of $Re_{T,flow}$ at elevated pressure. Due to the space limitation, we only present the iso-octane case. As to schlieren images of lean hydrogen and lean propane cases, we will report them elsewhere in the near future.

Figure 2(a) presents normalized turbulent flame speeds $(d\langle R\rangle/dt)/S_L^b$ as a function of $Re_{T,flame} = u'\langle R\rangle/\alpha = (u'/S_L)(\langle R\rangle/\delta_L)$ for the stoichiometric iso-octane/air mixture with $Le \approx 1.43$ at 423 K, where S_L^b is the laminar burning velocity on the burned side before density correction. All measured iso-octane flame speeds can be best represented by a power-law scaling, $(S_L^b)^{-1}d\langle R\rangle/dt = 0.09Re_{T,flame}^{0.5}$, regardless of different values of p = 1 ~ 5 atm and u' = 1.4 ~ 4.2 m/s. Same as Fig. 2(a), all measured turbulent flame speeds at different p = 1 ~ 5 atm and u' = 1.4 ~ 4.2 m/s for the lean propane/air mixture with $Le \approx 1.62$ at 298 K has a power-law scaling of $(S_L^b)^{-1}d\langle R\rangle/dt = 0.106Re_{T,flame}^{0.54}$, as shown in Fig. 2(b). Similarly, Fig. 2(c) is for lean hydrogen with $Le \approx 0.58$ at 298 K having a power-law scaling of $(S_L^b)^{-1}d\langle R\rangle/dt = 0.290Re_{T,flame}^{0.40}$. For comparison, Fig. 2(d) plots the above three power-law scaling relations together with that of our previous methane data ($Le \approx 1$) [10], in which all data are represented by $(S_L^b)^{-1}d\langle R\rangle/dt = A(Re_{T,flame})^B$. In [10] for methane data, A = 0.116 and B = 0.54 at T = 300 K, while A = 0.169 and B = 0.46 at T = 423 K. It is seen from Fig. 2(d) that there are large data variations, especially for the stoichiometric iso-octane data at 423 K which are much lower than the other data sets. This indicates a need to further pursue a better general correlation other than the above power-law scaling based on $Re_{T,flame}$.

Same as our previous methane results (see Fig. 4 in [10]), S_F is equal to the average value of $d\langle R\rangle/dt$ within 25 mm $\leq \langle R(t)\rangle \leq$ 45 mm. We convert all measured S_F data to turbulent burning velocities at $\langle c\rangle = 0.5$ ($S_{T,c=0.5}$) using the density correction and Bradley's mean progress variable $\langle c\rangle$ converting factor for schlieren spherical flames [17]. $S_{T,c=0.5} \approx (\rho_b/\rho_u)S_F(\langle R\rangle_{c=0.1}/\langle R\rangle_{c=0.5})^2$ for schlieren turbulent expanding spherical flames where the subscripts b and u indicate burned products and unburned reactants and $\langle R\rangle_{c=0.1}/\langle R\rangle_{c=0.5} \approx 1.4$ [17]. We discover that all scattering $S_{T,c=0.5}$ data with different values of Le together with previous methane/air mixtures at ϕ = 0.9 at T = 300 K and 423 K with $Le \approx 1$ can be all nicely collapsed onto a general correlation: $S_{T,c=0.5}/u' = 0.092(DaLe^{-1})^{0.5}$ with very small variations, as shown in Fig. 3, where the turbulent Damköhler number $Da = (L_I/u')(S_L/\delta_L)$.

5 Concluding Remarks

The normalized turbulent burning velocity $S_{T,c=0.5}/u'$ scales with $DaLe^{-1}$ to the one-half power, regardless of different fuels (i.e. iso-octane, hydrogen, propane, methane) at different values of Le, u', p, and T, showing fuel similarity at least for the same turbulent expanding spherical flames.

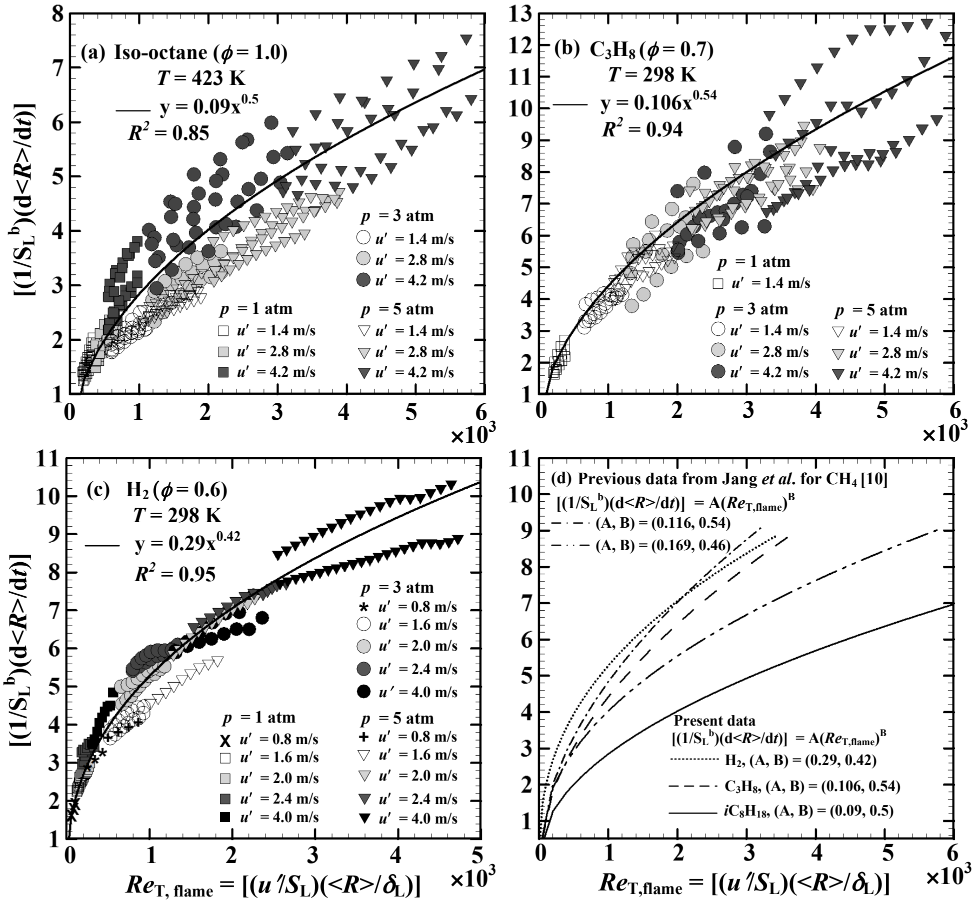

Fig. 2. Normalized turbulent flame speeds plotted against $Re_{T,\text{flame}}$. (a) Iso-octane with $Le \approx 1.43$. (b) Propane with $Le \approx 1.62$. (c) Hydrogen with $Le \approx 0.58$. (d) Comparisons of (a-c) together with previous methane data with $Le \approx 1$.

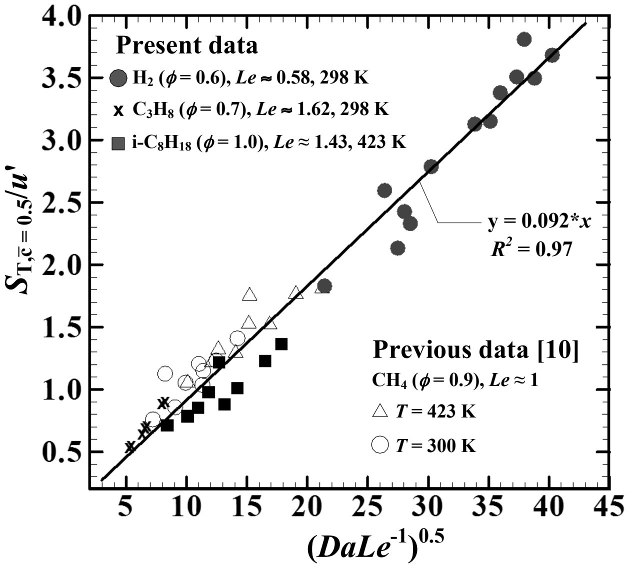

Fig. 3. The normalized turbulent burning velocity $S_{T,c=0.5}/u'$ scales with $DaLe^{-1}$ to the one-half power for various fuels with different Le and T under elevated pressure conditions over a range of u'.

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