Measurements of High-Pressure/Temperature Turbulent Burning Velocities of Lean and Rich Iso-Octane/Air Mixtures and Their Various General Correlations

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1 Abstract

This note reports the turbulent burning velocity (S_T) measurements of pre-vaporized liquid iso-octane/air mixtures over a range of the equivalence ratio (ϕ = 0.9 ~ 1.25) with $Le \approx 2.94 > 1 \sim Le \approx 0.93 < 1$ and the r.m.s. turbulent fluctuating velocity (u' = 0 ~ 4.2 m/s) under high pressure (p = 1 ~ 5 atm) and high temperature (T = 358K and 373K) conditions, where Le is the effective Lewis number. Experiments are conducted in a large dual-chamber, constant temperature/pressure, fan-stirred explosion facility capable of generating near-isotropic turbulence. Schlieren images of spherical expanding turbulent flames are recorded to obtain the growth of mean flame radii $<R(t)>$ and the observed flame speeds, S_F and/or $d<R>/dt$. S_F is the slope of $<R(t)>$ which is equal to the average value of $d<R>/dt$ within 25 mm $\leq <R(t)> \leq$ 45 mm. After density correction and using Bradley's mean progress variable $\bar{c}$ converting factor for Schlieren spherical flames, one can obtain S_T at $\bar{c}$ = 0.5, i.e. $S_{T,c=0.5} \approx (\rho_b/\rho_u)S_F(<R>_{c=0.1}/<R>_{c=0.5})^2$, where the subscripts b and u represent the burned and unburned mixture. At any fixed p, T, and u', $Le < 1$ flames propagate faster than $Le > 1$ flames with large scattering of $S_{T,c=0.5}$ data. When choosing proper scaling parameters from some existing general correlations and modifying them with the Le effect, these large scattering $S_{T,c=0.5}$ data can be well collapsed onto a single curve, regardless of different ϕ, Le, T, p, and u', showing self-similar propagation of turbulent spherical flames. It is found that the present liquid iso-octane $S_{T,c=0.5}$ data together with previous gaseous methane, hydrogen, and propane $S_{T,c=0.5}$ data can be represented by several modified general correlations that are compared and discussed based on their goodness of fitting.

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2 Introduction

This is the second paper emanating from a recent study on general correlations of high-pressure (p) and high-temperature (T) turbulent burning velocities (S_T) with the consideration of the effective Lewis number (Le) [1], where Le was estimated by the ratio between thermal diffusivity and mass diffusivity with the mass diffusivity being that of the deficient reactant and the abundant inert, i.e. $Le \approx Le_{fuel}$ (Le_{oxygen}) for lean (rich) mixture. In [1], values of S_T for various liquid and gaseous fuel/air mixtures, i.e. pre-vaporized stoichiometric iso-octane with $Le \approx 1.43$ at $T = 423$K, hydrogen at the equivalence ratio $\phi = 0.6$ with $Le \approx 0.58$ at 298K, and propane at $\phi = 0.7$ with $Le \approx 1.62$ at 298K, were measured, using the same dual-chamber, constant high-pressure/temperature, fan-stirred cruciform burner capable of generating near-isotropic turbulence as that used in [2] for gaseous methane fuel/air mixtures measurements. It was found that these very scattering S_T data with $Le < 1$ and $Le > 1$ [1] together with previous methane data at 300K/423K with $Le \approx 1$ [2] can be represented by four modified general correlations originally proposed by Bradley et al. [3], Kobayashi et al. [4], Shy et al. [5], and Chaudhuri et al. [6], when their scaling parameters were rescaling and grouping with Le^{-n}, each representing a single curve with small data scattering, where the power exponent n = 0.38 for the Bradley's correlation, n = 0.5 for the Shy's and the Chaudhuri's correlations, and n = 0.39 for the Kobayashi's correlation.

To further validate these four modified general correlations as briefly discussed in [1], the present study selects iso-octane as a fuel over a range of $\phi = 0.9 \sim 1.25$ with $Le = 2.94 > 1 \sim Le = 0.93 < 1$, the r.m.s. turbulent fluctuating velocity ($u' = 0 \sim 4.2$ m/s), and $p = 1 \sim 5$ atm at two different temperatures 358 K and 373 K to measure the wanted S_T data of lean and rich iso-octane/air mixtures. These iso-octane S_T data are of fundamental and practical importance, as iso-octane is the major surrogate component of gasoline and its burning velocities under high-p, high-T, high-u' relevant to high thermal efficiency gasoline engines and gas turbines are still rare (probably only available data were those reported by Lawes et al. [7] and by the authors [1]). Hence, these four modified general correlations are compared against the present lean and rich iso-octane S_T data with $Le > 1$ and $Le < 1$ alongside their goodness of fitting for scattering analyses.

3 Experimental Methods

The same experimental methodology as previous studies used in Refs. [1,2] is applied to measure S_T of iso-octane/air mixtures at $\phi = 0.9, 1.0, 1.25$ (or 1.2) with $Le \approx 2.94, 1.43, 0.93$ over a broad range of $u' = 0 \sim 4.2$ m/s and $p = 1 \sim 5$ atm at two different temperatures 358 K and 373 K. The reason to select these values of ϕ is to have roughly the same laminar burning velocity (S_L) for comparison, i.e. $\phi = 0.9$ ($S_L = 41$ cm/s) and $\phi = 1.25$ ($S_L = 40.2$ cm/s) at $T = 358$K; $\phi = 1.0$ ($S_L = 45$ cm/s) and $\phi = 1.2$ ($S_L = 44.6$ cm/s) at $T = 373$K. Other values of S_L are: $S_L = 45$ cm/s at $\phi = 1.0$ ($T = 358$K) and $S_L = 41.7$ cm/s at $\phi = 0.9$ ($T = 373$K).

Before a run, we first vacuum the heated 3D cruciform burner, then inject appropriate mole fraction of pre-vaporized iso-octane and air by means of the partial pressure method to the desired initial pressure, and mix well the iso-octane/air mixture by the two counter-rotating fans. Our dual-chamber, constant pressure, fan-stirred explosion facility can provide a uniform temperature distribution with less than 1^oC variation in the experimentation domain because of using a pair of heated perforated plates and 20 pieces of surface heaters [1,2]. A run begins by centrally-ignited the mixture using a pair of cantilevered electrodes to form a spark kernel that develops into spherical flame propagation which is recorded by high-speed Schlieren imaging to obtain the time evolution of the average flame radii $\langle R \rangle(t) = [A(t)/\pi]^{0.5}$, where $A(t)$ is the area enclosed by the laminar/turbulent flame front. The experimentation domain 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. For turbulent flame speeds calculation, $d\langle R\rangle/dt$ is directly obtained by the time differentiation on the raw data of $\langle R\rangle(t)$ in the range of 25 mm $\leq \langle R\rangle \leq$ 45 mm and S_F is determined as the slope of the best linear-fit of $<R>(t)$ within the same $\langle R\rangle$ range. It is found that the average of $d\langle R\rangle/dt$ is essentially equal to S_F [1,2]. Using the density correction and Bradley's mean progress variable $\bar{c}$ converting factor for Schlieren spherical flames, the turbulent burning velocity at $\bar{c}$ = 0.5, $S_{T,c=0.5} \approx (\rho_b/\rho_u)S_F(<R>_{c=0.1}/<R>_{c=0.5})^2$, can be obtained, where the subscripts b and u indicate burned products and unburned reactants.

4 Results and Discussion

Figure 1 shows the effects of *Le* and *p* on the emergence of small scale structures and the increase of average flame propagation rate at fixed u' with increasing *p* for both (a) laminar and (b) turbulent cases, where all images have almost the same $<R>$ = 35 mm. At any fixed *p*, the elapsed instants after ignition, as indicated in Fig. 1, show that *Le* < 1 flames (2nd and 4th columns) propagate much faster than *Le* > 1 flames (1st and 3rd columns). S_L decreases with increasing *p* (see the elapsed times in Fig. 1a), even though the flame at 5 atm appears more wrinkling due to the emergence of cellular structures all over the flame surface especially that at 5 atm and *Le* ≈ 0.93 < 1 (see 4th column image in Fig. 1a). For the turbulent case at constant u' = 1.4 m/s (Fig. 1b), the turbulent flame propagates faster with increasing *p* under both *Le* > 1 and *Le* < 1 conditions, where the turbulent wrinkled flames at 5 atm are full of very small scale structures. These fine structures are mainly due to the reduction of the thickness of the laminar flamelets (δ_L) at high pressure which promotes hydrodynamic instability, but they contribute little to the increase of S_T. This is because when the flow turbulent Reynolds number ($Re_{T,flow} = u'L_I/\nu$) can be kept constant, S_T actually decreases with increasing pressure, similar to S_L, showing a global response of burning velocities to the increase of pressure [5], where L_I and ν are the turbulent integral length scale and the kinematic viscosity of reactants. As such, the increase of S_T with increasing *p* at fixed u' is mainly due to the increase of $Re_{T,flow}$ at elevated pressure, since $\nu \sim \rho^{-1} \sim p^{-1}$.

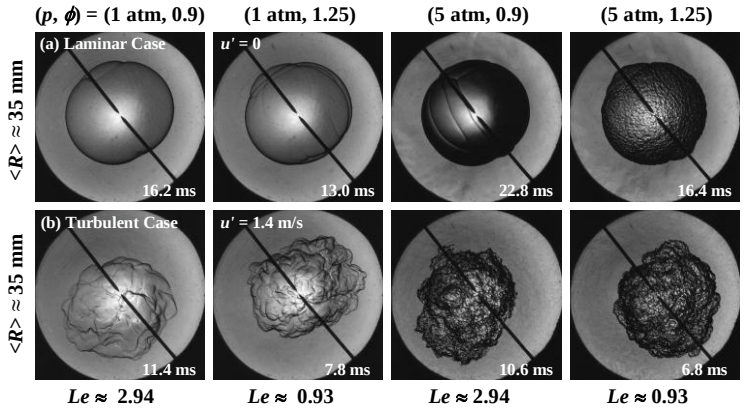

Figure 1. High-speed Schlieren imaging of lean and rich iso-octane/air expanding spherical flames at ϕ = 0.9 with *Le* ≈ 2.94 > 1 and ϕ = 1.25 with *Le* ≈ 0.93 < 1 at 358K. The images at almost the same $<R>$ ≈ 35 mm are selected for comparison having 110 mm x 110 mm view field. (a) Laminar case: u' = 0; (b) turbulent case: u' = 1.4 m/s.

Figure 2(a) reveals the relationship between the normalized turbulent burning velocity ($S_{T,c=0.5}/S_L$) and the normalized turbulent intensity (u'/S_L) for *Le* < 1 and *Le* > 1 iso-octane/air flames at 358 K over a range of

p = 1 ~ 5 atm. As expected, these data are very scattering with very poor goodness (R^2 = 0.37 ~ 0.51), showing a strong influence of Le on $S_{T,c=0.5}$. Again, $S_{T,c=0.5}/S_L$ decreases with increasing Le at any fixed u'/S_L. The increase of $S_{T,c=0.5}/S_L$ with u'/S_L is not linear due to the bending at higher u'/S_L. Figure 2(b) presents laminar and turbulent burning velocities as a function of temperature at four different values of u' for the stoichiometric iso-octane/air mixture at 1 atm. Both values of S_L and $S_{T,c=0.5}$ increase with increasing T, representing by the power law as indicated in Fig. 2b, where T_0 = 298K.

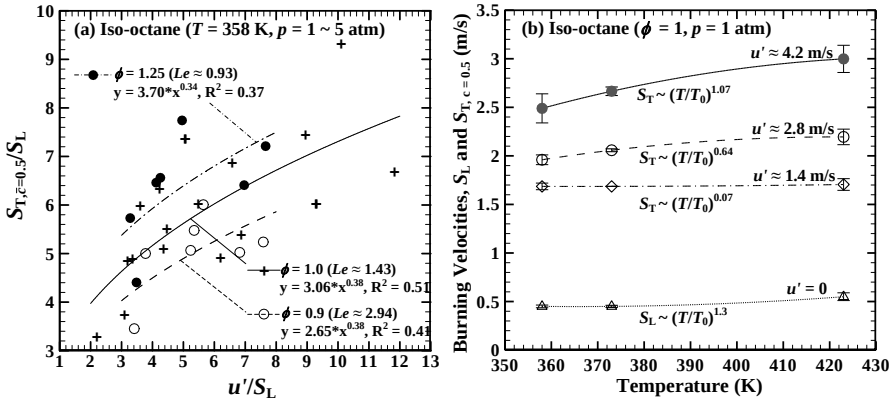

Figure 2. (a) Normalized turbulent burning velocities at $\bar{c}$ = 0.5 plotted against turbulent intensities (u'/S_L). (b) Effect of temperature on flame speed of stoichiometric iso-octane at 1 atm

Our present lean, stoichiometric, and rich iso-octane data at different elevated pressures and temperatures together with previous data for various gaseous fuels [1,2] and the stoichiometric iso-octane/air mixture at 423K [1] are used to validate the aforesaid four general correlations modified with the effect of Le, as listed below, alongside their goodness of fitting as shown in Fig. 3.

Modified correlation of Bradley et al.: $S_{T,c=0.5}/u' = 0.43(KLe)^{-0.38}$; $R^2 = 0.87$ (1)

Modified correlation of Shy et al.: $S_{T,c=0.5}/u' = 0.09(DaLe^{-1})^{0.5}$; $R^2 = 0.97$ (2)

Modified correlation of Chaudhuri et al.: $S_{T,c=0.5}/S_L = 0.25(Re_{T,flame}Le^{-1})^{0.5}$; $R^2 = 0.89$ (3)

Modified correlation of Kobayashi et al.: $S_{T,c=0.5}/S_L = 2.72[(u'/S_L)(p/p_0)Le^{-1}]^{0.39}$; $R^2 = 0.91$ (4)

In Eq. (1), $K = 0.25(u'/S_L)^2(Re_{T,flow})^{-0.5}$ was a stretched factor. It should be noted that the original version of Eq. (1) was limited in the range of KLe between 0.01 and 0.63 [3]. When KLe < 0.01 and/or KLe > 0.63, Bradley's correlation had large data scattering due to the logarithmic plots of u_t/u'_k (or S_T/u') against KLe (please see Fig. 5 of Ref. [3]). Da in Eq. (2) was the turbulent Damköhler number, defined as the product of $(L_I/u')(S_L/\delta_L)$. In Eq. (3), the turbulent flame Reynolds number $Re_{T,flame} = u'<R>/\alpha$ where α was the thermal diffusivity. p_0 = 1 atm in Eq. (4).

Results show that these very scattering $S_{T,c=0.5}$ data with Le < 1 and Le > 1 can be well represented by the above four modified correlations, regardless of different fuels, ϕ, p, T, u' and Le used, showing self-similar turbulent flame propagation. The goodness of fitting (R^2) in each of four modified equations is quite good, where $R^2 \geq 0.87$.

In short, these four general correlations modified with the effect of Le as presented in Eqs. (1-4) should be useful to our further understanding of high-pressure/temperature turbulent burning velocities.

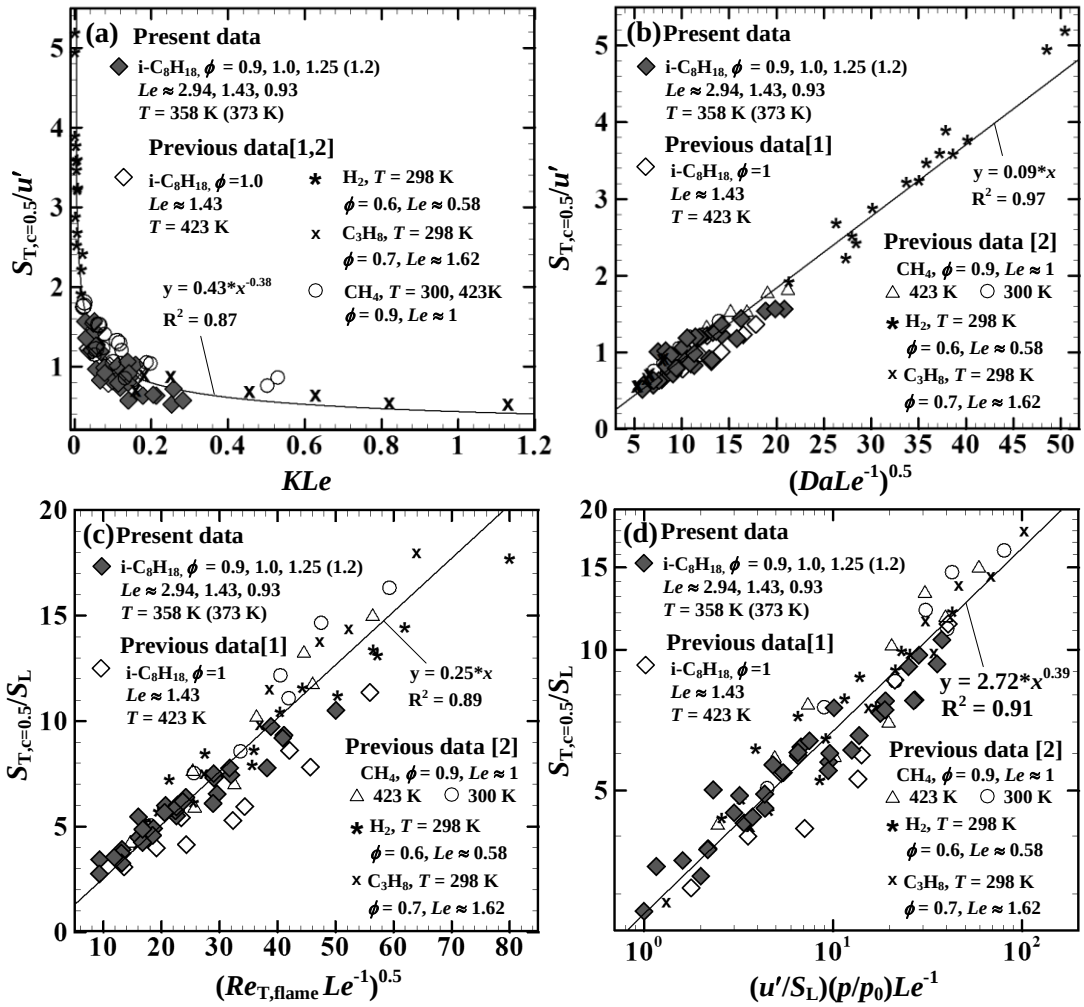

Figure 3. Normalized turbulent burning velocities for various liquid and gaseous fuels plotted against four scaling parameters: (a) KLe;; (b) $(DaLe^{-1})^{0.5}$; (c) $(Re_{T,flame}Le^{-1})^{0.5}$; (d) $(u'/S_L)(p/p_0)Le^{-1}$.

5 Concluding Remarks

Turbulent burning velocities of pre-vaporized iso-octane/air mixtures having $Le < 1$ and $Le > 1$ are measured under elevated pressures and temperatures relevant to gasoline engine or gas turbine conditions. Four modified general correlations with the consideration of the Lewis number effect are proposed, each of them all showing reasonably nice goodness of fitting, which should be useful to estimate the engine stability and reactivity under varying parameters.

References

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