Comparison of Lean Methane and Syngas Turbulent Burning Velocities and Their Dependence on Damköhler Number at Elevated Pressures

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1 Introduction

High-pressure turbulent premixed combustion at large Reynolds numbers ($Re_T \equiv u'L_I/\nu$) is of importance to many industrial applications, such as internal combustion engines as the major driving force behind modern combustion research, where u' and L_I are the r.m.s. turbulent fluctuation velocity and the integral length scale of turbulence and ν is the kinematic viscosity of reactants. Recently, Shy and his co-workers [1-3] adopted a very large high-pressure, double-chamber, fan-stirred cruciform burner with perforated plates (see Fig. 1) capable of generating intense near-isotropic turbulence with negligible mean velocities to measure high-pressure turbulent burning velocities (S_T) of lean methane and syngas spherical expanding flames. Such a novel facility not only allows S_T measurements at elevated pressure (p) up to 1.2 MPa, but also it can provide a controllable turbulent environment in which the product of $u'L_I$ can be controlled in proportion to the decreasing ν due to the increase of p. Shy et al. [2,3] have found that, contrary to popular scenario for turbulent premixed flames at elevated pressure, S_T decreases similarly as laminar burning velocities (S_L) with increasing p in minus exponential manners when values of Re_T are kept constant. They have also found that at any constant p ranging from 0.1 MPa to 1.0 MPa, S_T/S_L increases noticeably with increasing Re_T varying from 6,700 to 14,200. This finding is important, because many studies in the past merely looked at the promotion effect of increasing pressure on S_T due to the enhancement of flame instabilities at elevated pressure without any consideration of the concurrent influence of Re_T elevation. Note that because the kinematic viscosity is inversely proportional to the fluid density, pressure elevation plays an important role in increasing Re_T.

But there is a discrepancy on the power law dependence of turbulent burning velocities to the turbulent Damköhler number (Da) between lean methane [2] and syngas [3] fuels, where $Da = (L_I/u')(S_L/\delta_F)$, the laminar flame thickness is equal to $\delta_F \approx \alpha/S_L$ and α is the thermal diffusivity of unburned mixture. For the lean methane flames, $S_T/u' \approx 0.12Da^{0.5}$ [2] that supports a distributed reacton zone model anticipated by Ronney [5], while $S_T/u' \approx 0.54Da^{0.25}$ for the lean syngas flames [3] which supports a theory predicted by Zimont [6]. Hence, the objective of this note is to propose a physical mechanism in attempt to explain what causes the aforesaid discrepancy. It shoud be noted that all properties and parameter ranges given in this note, including u', L_I, S_L, S_T, ν, α, Re_T, and Da, can be found in the table of Ref. [2] for lean methane flames and in Refs. [3,4] for lean syngas flames.

2 Experimental Methods

Figure 1 shows the high-pressure, double-chamber explosion facility with the Schlieren optical image arrangement, where the large inner cruciform burner is lodged in a huge high-pressure outer chamber. Two 45^0-alligned conventional spark-electrodes with sharp ends are placed at the centre of the inner burner to ignite combustible mixtures inside under fixed p and Re_T conditions. For detail treatment of the facility, the reader is directed to Ref. [2].

In this study, a high-speed Schlieren imaging technique is applied to visualize these centrally-ignited, outwardly-propagating spherical premixed flames using both lean methane mixtures at the equivalence ratio of $\phi = 0.8$ and lean syngas (35%H_2/65%CO) mixtures at $\phi = 0.5$. Figure 2 presents typical Schlieren images of spherical expanding premixed flames at $p = 0.5$ MPa for both laminar and turbulent cases, each case including the aforesaid two mixtures for comparison. Note that these centrally-ignited, expanding spherical flames are recorded by the Phantom v310 CMOS camera that is operated at various frame rates from 2,000 frames/s to 11,000 frames/s depending on expanding flame speeds with the same spatial resolution of 512 x 512 pixels. From these time evolutions of spherical expanding flames, flame speeds can be determined. Figure 3 shows the effective flame radii (r_{eff}) as a function of time (t) for the turbulent case in Fig. 2, where the inset is the contours of syngas flames at four different times. The area of the flame contour is the product gas projection area (A_{SG}) that is used to determine r_{eff}, by which $r_{eff} = (A_{SG}/\pi)^{0.5}$. Then the turbulent flame speed (S_F) is determined as the slope of the linear-fit line for the associated r_{eff}-t data except those with $r_{eff} < 25$ mm and $r_{eff} > 45$ mm (see Fig. 3), where data of $r_{eff} > 50$ mm are not shown. The requirement of $r_{eff} \geq 25$ mm is to avoid any possible influences from the course of spark ignition and its subsequent flame kernel development at the early stage. It is worthy of noting that our cruciform burner is very spacious having a spherical radius of at least 173 mm measured from the centre of the spark electrodes to the nearest wall. This large radius is more than 3.8 times than the outer cutoff $r_{eff} = 45$ mm, so that the measured turbulent spherical expanding flames are not influenced by the chamber walls. Thus, a quasi-steady S_F can be determined within 25 mm $\leq r_{eff} \leq$ 45 mm, as can be seen from Fig. 3 for both lean methane and syngas flames. After correcting the burned gas density (ρ_b) back to the unburned one (ρ_u), the wanted S_T can be thus determined by the relation of $S_T = (\rho_b/\rho_u)S_F$. As already discussed in [2], S_T can be influenced by different reactant flow configurations and it is logical to select the mean progress variable $\bar{c} = 0.5$ as the standard flame $\bar{c}$ position for the determination of S_T [2]. In order to determine values of S_T at $\bar{c} = 0.5$ from the obtained S_T which is equivalent to $S_{T,\bar{c}=0.1}$ [2], we apply the relation of the radius ratio between $\bar{c} = 0.1$ and $\bar{c} = 0.5$, that is $r_{\bar{c}=0.1} / r_{\bar{c}=0.5} \approx 1.4$ [2]. Based on the conservation of mass burning rate, $S_{T,\bar{c}=0.5} / S_{T,\bar{c}=0.1} = (r_{\bar{c}=0.1} / r_{\bar{c}=0.5})^2$ from the present turbulent spherical expanding flame data, where $S_{T,\bar{c}=0.5}$ is the turbulent burning velocity obtained at $\bar{c} = 0.5$ whose $r_{eff} = r_{\bar{c}=0.5}$. Hence, all S_T data discussed upon here are values of $S_{T,\bar{c}=0.5}$.

3 Results and Discussions

As can be seen in Fig. 4, there are two differences between the parameterizations of the experimental data obtained by us from the lean methane and syngas flames. First, the ratio of S_T/u' is larger for the latter fuel. This effect can be attributed to the Lewis number (Le) and preferential diffusion phenomena of the lean syngas fuel having a lower value of Le (< 1), which are well known for their important role in premixed turbulent combustion even at high Reynolds numbers, as already discussed in detail elsewhere [7,8]. Because the diffusion coefficients of methane and oxygen are approximately equal to one another and to the thermal diffusivity of flammable methane-air mixtures ($Le \approx 1$), such preferential diffusion phenomena are therefore only weakly pronounced in lean methane flames. On the other hand, when turbulent combustion of lean syngas-air mixtures is considered, the enhancement of turbulent burning velocities is further promoted due to a higher diffusivity of H_2 where Le is much less than unity.

Secondly, the power exponent q in the scaling $S_T \sim u'Da^q$ is larger for lean methane flames by a factor of two than that of lean syngas flames. Because both lean methane and syngas flames were investigated by varying u', L_I, S_L, Re_T, Da, and pressure approximately (or exactly) in the same ranges, the obtained difference in q is also associated with Le and preferential diffusion phenomena, which are much stronger pronounced in the lean syngas flames as compared with the methane ones. Since the present experiments were done in intense turbulence characterized by large Re_T, it is tempting to assume that local combustion quenching by high stretch rates plays a role in these flames resulting in the bending of the measured dependencies of S_T on u' [8]. It is known [7-9] that premixed flames characterized by a higher diffusivity of the deficient reactant and a lower Le (e.g., lean syngas-air mixtures) can survive under the influence of significantly stronger stretch rates as compared with flames characterized by $Le \approx 1$ (e.g., lean methane-air mixtures). Therefore, it is likely that the lean methane-air flames are substantially affected by the local combustion quenching, at least in sufficiently intense turbulence, whereas the lean syngas flames are not. Indeed, the scaling of $S_T \sim u'Da^{0.5}$ of our methane data indicates a relatively weak dependence of S_T on u', which can be attributed to a strong bending effect, while the scaling of $S_T \sim u'Da^{0.25}$ of our syngas data agrees very well with the scaling theory obtained by Zimont [6] and well supported by many experimental studies of moderately turbulent flames associated with weakly pronounced local combustion quenching [10].

To further assess this explanation, let us assume that the discussed power exponent q is increased when the probability of local flamelet quenching is increased. Because an increase in this probability is commonly associated with an increase in the Karlovitz number (Ka) [7-9], the above assumption means that $q = q(Ka)$ is an increasing function. Here, $Ka = 15^{1/2}\tau_c u'/\lambda \approx 0.68 Re_T^{1/2}/Da$, the chemical time scale τ_c is equal to δ_F/S_L, and λ is the Taylor microscale of turbulence. A step function, $q = q_1$ if $Ka < Ka^*$ and the quenching plays a minor role or $q = q_2$ if $Ka > Ka^*$ and the quenching plays an important role where $q_1 < q_2$, could be the simplest example of $q = q(Ka)$. Results of processing the same methane data in Fig. 4 invoking such a step function are shown as the two solid curves in Fig. 5, with filled and/or opened circles corresponding to $Ka > Ka^*$ and/or $Ka < Ka^*$, of which the critical $Ka^* = 0.85$ is determined from the constraint of the minimum scatter of the experimental data. It is encouraging that the obtained critical value is close to unity. Moreover, the use of the step function has substantially (by a factor of 1.5) reduced the scatter of the experimental data and has made $q_1 \approx 0.3$ significantly closer to the value of $q \approx 0.25$ determined earlier [3] for our lean syngas flames. The remaining difference in $q_1 \approx 0.3$ and $q_{syngas} \approx 0.25$ could be associated with the scatter of the experimental data and with the limitation of the step approximation of a continuous function $q = q(Ka)$. More experimental data are required in order to determine this function more accurately.

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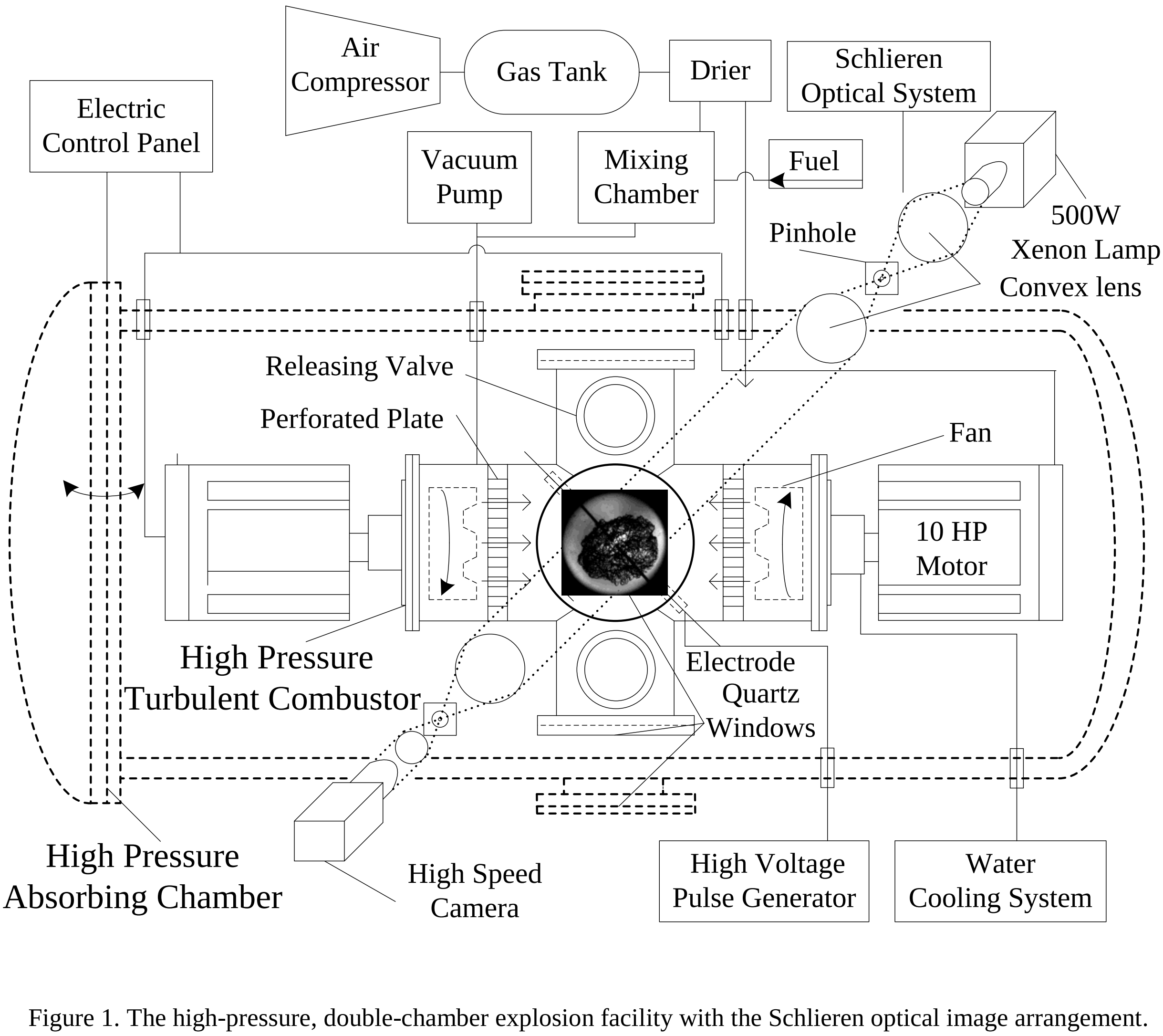

Figure 1. The high-pressure, double-chamber explosion facility with the Schlieren optical image arrangement.

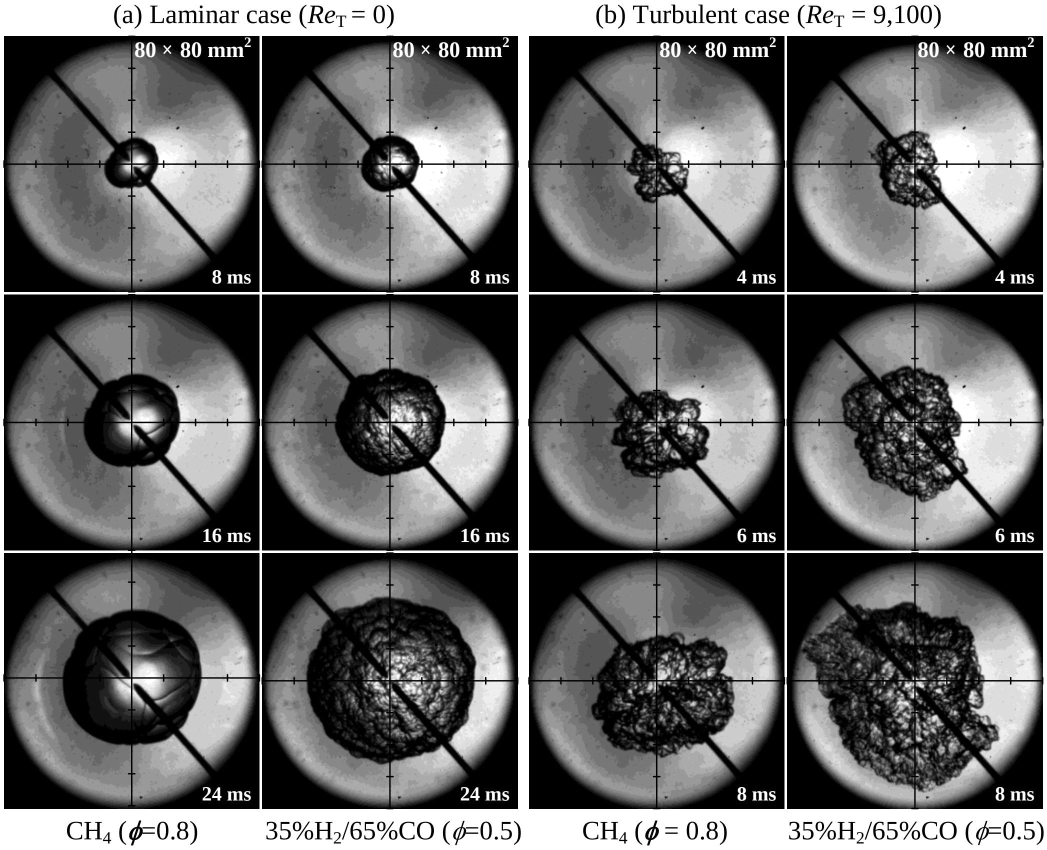

Figure 2. Typical Schlieren images of spherical expanding laminar and turbulent premixed flames using lean methane and syngas fuels at p = 0.5 MPa.

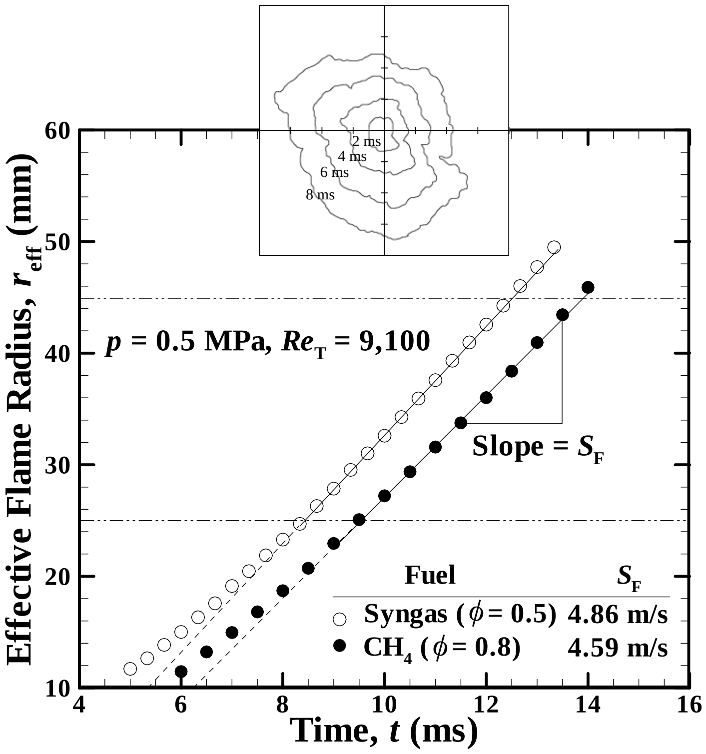

Figure 3. Typical effective flame radii as a function of time for S_T determination.

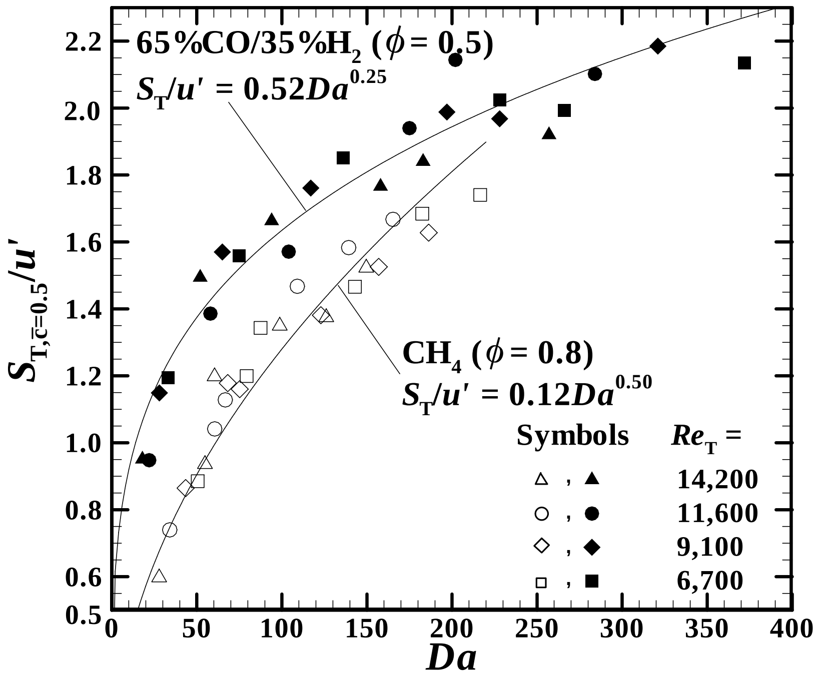

Figure 4. Comparison of normalized turbulent burning velocities between lean methane and syngas fuels plotted against the turbulent Damköhler number over a range of p from 0.1 MPa to 1.0 MPa with constant Re_T varying from 6,700 to 14,200.

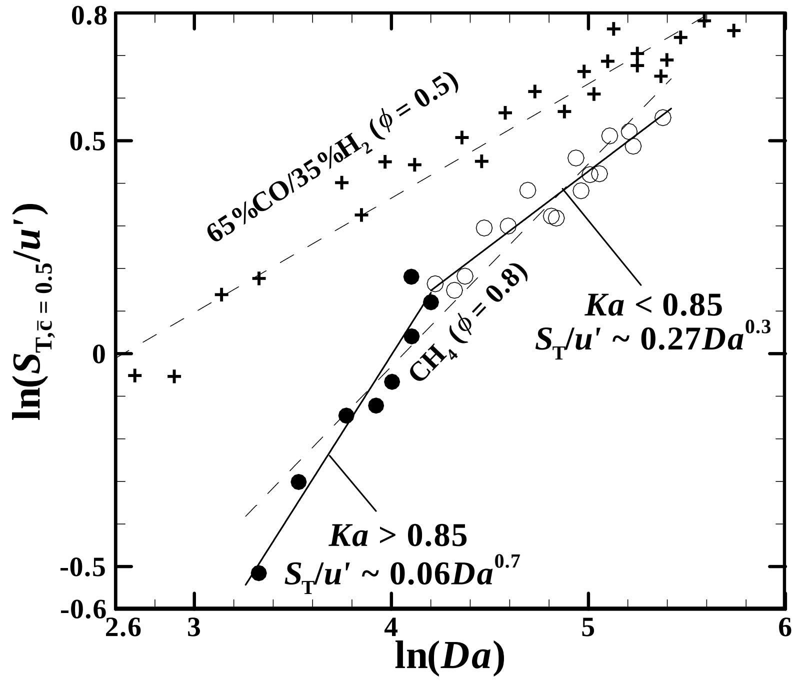

Figure 5. Same data as Fig. 4, but re-fitted the methane data into two groups using the step function $q = q(Ka)$, where $q_1 = 0.3$ if $Ka < 0.85$ and $q_2 = 0.7$ if $Ka > 0.85$.