# Turbulent Burning Velocities of $CH_4$-Air Mixtures In A New Turbulent Flow System

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**Abstract**

Turbulent burning velocities of methane-air mixtures at stoichiometric burning are measured in a new turbulent flow system that is designed to fulfill the homogeneity requisite, minimize the buoyancy effect, and eliminate the pressure rise due to burning in a constant-volume vessel. This apparatus has two cylindrical vessels with a cruciform shape. The long vertical vessel can provide a stably downward propagating premixed flame at one atmosphere, while the horizontal vessel is equipped with two identical counter-rotating eight bladed fans at each end, driven by electric motors which are synchronized to the same speed. The motor-driven fans with controllable frequencies up to 7,620 rpm can generate two intense counter-rotating large vortical streams. Each of both turbulent streams passes through a specially designed perforated plate, intertwining with each other. Thus, a *roughly* isotropic turbulence with large turbulent intensities (up to 450 cm/s) located in the core region between two perforated plates can be generated, as verified by LDV measurements. Three different methods, including a two-camera method, the hot-film anemometer, and an ion-probe method are used to measure turbulent burning velocities. It is found that when the normalized turbulent intensity ($u'/S_L$) is less than unity, values of the normalized turbulent burning velocity ($S_T/S_L$) increase linearly with $u'/S_L$, where $S_L$ is the laminar burning velocity. The $S_T/S_L$ plots tend to depart from the linearity as $u'/S_L > 1$ and bend gradually towards the horizontal for larger $u'/S_L$ up to 11. The turbulent Reynolds number does not have a strong effect on $S_T/S_L$ at a fixed $u'/S_L$. These results are compared to earlier premixed gaseous experiments using different apparatuses.

## Introduction

Premixed turbulent combustion is of practical importance, since turbulence can increase the mass consumption rate of reactants to a value well above its laminar burning velocity [1]. One important facet of premixed turbulent combustion is on the effects of turbulent intensity ($u'$) to the turbulent burning velocity ($S_T$) that influence virtually all important properties of premixed turbulent flames. $S_T$ is ordinarily defined as the volume flux through the evolving surface per unit projected cross-sectional area in the direction of propagation. Concerning the effect of $u'$ on $S_T$, there is still no general consensus on any point except that turbulence should increase $S_T/S_L$. Whether can a steady state value of $S_T$ exist? Whether does the turbulent Reynolds number ($Re_T = u'L_I/\nu$; $L_I$ is the integral length scale of turbulence and $\nu$ is the kinematic viscosity of reactant) have an effect on $S_T/S_L$ at a given $u'/S_L$? Whether do the $S_T/S_L$ plots have constant slope or bend towards the horizontal at high $u'/S_L$? This paper attempts to address these questions.

Several researchers had focused on how to generate a turbulent flow field that is roughly homogeneous for investigating flame-turbulence interactions at higher $Re_T$ and $u'/S_L$. These experiments included, for example, (1) constant-volume fan-stirred explosion vessel flames [1,2], (2) weak-swirling stabilized flames [3], and (3) turbulent Taylor-Couette (TC) flames [4]. Unfortunately, these flows [1,3] still suffer various degrees of inhomogeneity, unsteadiness, or having significant mean flow velocity or mean strain. Although the TC flow with both cylinders rotating can generate modes similar to featureless turbulence, there was an intrinsic disadvantage of this flow. Because the TC annulus gap was very narrow, having only a width of at most one or two integral length scales, and the energy spectrum of the TC flow was different to that of isotropic turbulence. Thus, there is a need to further devise an idealized turbulent flow system for benchmark experimental data in studying premixed turbulent combustion.

Accurate measurements of turbulent burning velocities are extremely difficult to obtain, because heat release at the flame front can induce global as well as local changes of the turbulent flow field. This is the reason why the large scattering data of $S_T/S_L$ are commonly observed even at a fixed $u'/S_L$ in a given flow configuration [1,4]. The stabilized turbulent flames [3] had a large flame brush thickness (typically 5 cm estimated from Fig. 6 in [3]), which in turn clouded the accuracy of $S_T$ measurements. Also, there are large experimental uncertainties in measuring $S_T$ using the classic hot-wire anemometer [1], since the hot-wire is very fragile and easily broken even before the flame arrived, as to be discussed. More uncertainties for a freely propagating turbulent flames in TC flow [4] are expected using the video-camera operated at 30 Hz (not counted a 5 cm/s mean upward speed of the reactants applied). In this study, a new turbulent flow system is introduced to fulfill the homogeneity requisite, minimize the buoyancy effect induced by heat

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release, and avoid the pressure rise due to burning in a constant-volume vessel. Turbulence characteristics of this new burner were obtained using two-component fiber laser Doppler velocimetry [5]. Three different methods in measuring $S_T$ were applied, including a two-camera method, the hot-film anemometer, and an ion-probe method. Results for values of $S_T/S_L$ over a wild range of $u'/S_L$ are presented and compared to previous results using different apparatuses.

# Experimental

Figure 1 is a sketch of the experimented setup. Two identical counter-rotating eight bladed fans at each end of the horizontal vessel (Fig.1) are driven by electric motors which are synchronized to the same speed (up to 7,620 rpm with the water cooling system for both motor shafts). The fans generate two intense counter-rotating large vortical streams, each of both vortical streams passing through a perforated plate, breaking large vortical structures into smaller vortices, and intertwining with each other. Thus, a *nearly* isotropic turbulence with large turbulent intensities, up to 450 cm/s, located in the core region between two perforated plates, is generated as verified by extensive LDV measurements [5]. For the detail treatment on turbulence characteristics and its statistics, the reader is directed to [5].

This study conducts premixed turbulent combustion experiments of $CH_4$-dry air mixtures at stoichiometric burning condition in the above-mentioned apparatus. Three different methods in measuring $S_T$ are applied. The key is to measure the time that the turbulent premixed flame takes to consume all reactants in a given volume as sketched as the shaded region in Fig. 1. (1) A two-camera method: As shown on Fig. 2, we apply the bottom camera to record the time ($t_1$) that a run takes from the beginning of ignition to the end of burning, displaying instantaneous photographs at seven sequent times. Simultaneously, the front camera records the mean flame position observed from the rectangular window (see Fig. 1) to obtain its elapse time ($t_2$) from the initial ignition. We then measure the volume flux of the shaded region (Fig. 1) during the time period of ($t_1$ - $t_2$). Thus, $S_T$ is determined as such a volume flux divides by an effective area ($A_{eff} = (A_V+A_H)/2$, where $A_V$ and $A_H$ are the cross-sectional area of the vertical and horizontal vessels, respectively). (2) The hot-film anemometer: We use two hot films (TSI-1201; 0.2 mm in diameter), positioned at point “a” and “c” (Fig. 1) in attempt to measure the corresponding consumption rate. The hot-film probe is highly sensitive, but unfortunately it is extremely vulnerable for turbulent reacting flows (the hot-wire probe is even worse). After a turbulent combustion run, the probe is always damaged. Moreover, when the temperature of the hot-film exceeds over 250$^o$C, the analyzer (IFA-100) will stop to receive data, switching itself to the standby status, until the temperature is below 250$^o$C. Thus, it is impossible to measure $S_T$ accurately using the hot-film method without a very rigorous calibration procedure. (3) The ion-probe method: It has long been recognized that the abnormal ionization occurs within flames, and concentrations of ions in the reaction sheet could be several orders larger than that in high temperature products [6,7]. A carefully-shielded ion-probe that has the large signal amplitude and fast frequency response is quite pertinent for the identification of flame front propagation. It should be noted that the careful shielding and grounding procedures for ion-probe measurement in turbulent reacting flows are essential, because the frequency converters (Fig. 1) can generate very large electromagnetic noises. Two ion-collecting electrodes, made of pure platinum wires of diameter 0.2 mm, are located at levels “a” and “c” (Fig. 1) respectively, measured the mean propagation rate of turbulent premixed flames. Though the smaller diameter (< 0.2 mm) of the platinum wire has faster response, it is readily broken during turbulent combustion so is not used. The circuit loop of platinum wires, supported by two ceramic tubes, can detect ion current signals that are converted into voltage signals via a 450 $k\Omega$ resistor and stored in a 330 kHz data acquisition card (PCL-1800). It is found that an equal gap of 1 mm between two parallel platinum wires (tightened) with length of about 4 cm has the highest signal to noise ratio. Also, we have tested the sensitivity of the electrodes’ length (0.5 cm ~ 6 cm) on the signal output, and found that the lengths of 3.5 cm ~ 5.2 cm are suitable for our purpose in measuring $S_T$. Note that the point ion-probe is good for the flame thickness measurements [6], but not appropriate for current $S_T$ measurements.

In the present study, the turbulent Reynolds number can be varied from 140 to 14,620. The ratio of $u'/S_L$ ranges from 0.34 to 11.55, corresponding that the Karlovitz number, $Ka = (u'/S_L)^{1.5}/(L_I/\delta_L)^{0.5}$, is from 0.01 to 1.3 where $\delta_L$ is the laminar flame thickness. Thus, the investigated combustion phenomena may lie somewhere between the “corrugated flamelet” and “distributed” regimes in the Borghi diagram. Figure 2 shows variations of the energy-weighted effective turbulent intensity (q), turbulent length scales, and turbulent Reynolds numbers with the two-fan frequency. A run began by igniting premixed reactants and simultaneously opening four large venting valves at the top of the cruciform burner, developing a stably downward propagating flame front.

# Results and Discussion

As the flame propagates downward and interacts with turbulence in the region of interest, the overall images of flame wrinkling can be observed, as shown in Fig. 2 (right). In it three instantaneous premixed-flame propagation photographs for $u'/S_L = 0.7$ are present, where the field of view (the front window) is 100 mm in diameter. At low turbulent intensities, the boundary of the propagating flame front can be distinctly identified. Essentially steady propagation of a wrinkled flame surface is found in the region of interest. In the near future, we shall report the spatial statistics of these propagating flame fronts extracted from 2-D images using the laser tomography with a high-speed camcorder (8,000 frames/s) and statistical methods reported previously in [8,9].

Figure 4 presents a comparison of laminar burning velocities of $CH_4$-air mixtures vs. the equivalence ratio, including the present ion-probe measurements ($S_{L,Ion}$), results of Andrews and Bradley [10] ($S_{L,AB}$), and those obtained by Vagelopoulos et al. [11] ($S_{L,VEL}$). The inset in Fig. 4 is typical signals for the present ion-probe measurement. Two ion probes are positioned at levels “a” and “c” with 37 cm apart. The upper probe (channel 1) detects an essentially flat, very thin premixed flame as can be seen from its signal spike. As the flame enters the region of interest, it wrinkles due to an area expansion of the apparatus. The signal in the channel 2 is not as sharp as in the channel 1, indicating that the flame there has a brush thickness. The time difference between two signals can be readily measured without ambiguity, which in turn determines values of $S_L$. The present $S_{L,Ion}$ (I) in Fig. 4 is larger than $S_{L,VEL}$ by roughly 35 %, whereas the present $S_{L,Ion}$ (II) is in good agreement with $S_{L,VEL}$. Note that the disagreement between $S_{L,AB}$ and $S_{L,VEL}$ is ranging from 12 % to 75 %.

The normalized turbulent burning velocities as a function of the normalized turbulent intensities are shown on Fig. 5, including the two-camera and the ion-probe data as represented by symbols of the solid square and the empty circle, respectively. Here we choose the averaged laminar burning velocity ($S_L$ = 40 cm/s at $\phi$ = 1) for normalization of $S_T$ and $u'$ or q. Again, $u'$ is the characteristic turbulent intensity in the direction of propagation and q is the overall (energy-weighted) turbulent intensity in all three direction. At a fixed f, several runs at the same conditions are taken to evaluate the experimental uncertainties. Similar to other previous experiments [1,4], the large scattering data of $S_T/S_L$ are observed when the two-camera method is applied. For values of $u'/S_L$ greater than three, we plot only the maximum and minimum data points of $S_T/S_L$ at a fixed value of $u'/S_L$ obtained by the two-camera method for clarity. As can be seen in Fig. 5 (see the inset), the present ion-probe method offers a good way in measuring $S_T$ accurately because of its simplicity and small experimental uncertainty.

Also shown on Fig. 5 are some experimental results obtained from earlier studies using different apparatuses. The first is the “unsteady-bomb” result by the Leeds’ group led by Prof. Bradley [2] in which the plots were obtained from “smoothing” an extensive compilation of experimental data characterizing by the Karlovitz, Lewis, and Reynolds numbers. For simplicity, we plot only the “smoothing” lines of $Re_T/(Le)^2$ from 10 to 3000 for $u'/S_L$ up to 12. The second and third results to compare are respectively stabilized flames with $u'/S_L$ up to 2 and $Re_T < 500$ [12] and weak-swirling stabilized flames for $u'/S_L$ up to 8 and $480 < Re_T < 1600$ [3]. The fourth experiment is for flame propagation in Taylor-Couette flow where values of $u'/S_L$ were up to 10 and $70 < Re_T < 350$ [4]. In comparison with these results, it is found that at low values of $u'/S_L$ ($\leq$ 1), all measurements of turbulent burning velocities are very close, regardless of different forcing conditions applied. By carefully examining these results for $u'/S_L \leq 1$, it can be seen (Fig. 5) that our ion-probe data are in very good agreement with that abstained by Bedat & Cheng [3], in which their correlation can be represented: $S_T/S_L = 1 + 2.5(u'/S_L)$. For $u'/S_L > 1$, our present results on the normalized turbulent burning velocities are lower than those reported by Bedat & Cheng [3] and Aldredge et al. [4]. Such a difference in values of $S_T/S_L$ among these experiments increases with $u'/S_L$. Obviously, our results of turbulent burning velocities show a strong bending effect that occurs beyond $u'/S_L \cup 1$. This differs drastically from the results of Bedat and Cheng [3] that revealed no bending effect, but consistent with the results of Bradley [2]. Recently, Aldrege et al. [4] also observed the bending effect using a Taylor-Couette apparatus. Thus, our present result strongly supports the existence of the bending phenomena, regardless of different forcing conditions applied in the above three different experiments. For $u'/S_L > 1$, the flame propagation may be modified by small-scale turbulence, causing the bending effect in which values of $S_T/S_L$ decrease below the Huygen’s propagation velocity at fixed values of $u'/S_L$, as suggested by Ronney & Yakhot [13]. From the first look on Fig. 5, our normalized turbulent burning velocities are all in the data domain obtained by Bradley [2], showing a reasonable agreement except that there is a large difference on the effect of turbulent Reynolds number to turbulent burning velocities between two experimental results. The present results show that the turbulent Reynolds number does not have a strong influence on $S_T/S_L$, in contrast to previous findings [2].

# References


[1] R. Abdel-Gayed, D. Bradley, and M. Lawes, Proc. R. Soc. Lond. *A*, 414:389-413, 1987.
[2] D. Bradley, Twenty-Fourth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 247-262 (1992).
[3] B. Bedat and R. K. Cheng, Combust. Flame, 100:485-494, 1995.
[4] R. C. Aldredge, V. Vaezi, and P. D. Ronney, Combust. Flame, 115:395-405, 1998.
[5] S. S. Shy and W. K. I, A Turbulent Flow System for Investigating Premixed Turbulent Combustion Processes. 11th International Symposium on Transport Phenomena, Hsinchu, Taiwan, Nov. 29 – Dec. 3, 1998.
[6] T. Suzuki, T. Hirano, and H. Tsuji, Seventeenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 289-297 (1979).
[7] C. K. Lin, M. S. Jeng, and Y. C. Chao, Exp. in Fluids, 14:353-365, 1993.
[8] S. S. Shy, R. H Jang, W. K. I, and K. L. Gee, Twenty-Sixth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 283-289 (1996).
[9] S. S. Shy, W. K. I, E. I. Lee, T. S. Yang, Experimental Analysis of Flame Surface Density Modeling for Premixed Turbulent Combustion Using Aqueous Autocatalytic Reactions, To appear in Combust. Flame, 1999.
[10] G. E. Andrews and D. Bradley, Combust. Flame, 19:275-288, 1972.
[11] C. M. Vagelopoulos, F. N. Egolfopoulos, and C. K. Law, Twenty-Fifth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, pp. 1341-1347 (1995).
[12] R. K. Cheng and I. C. Shepherd, Combust. Flame, 85:7-26, 1991.
[13] P. D. Ronney and V. Yakhot, Combust. Sci. Technol., 86:31-43, 1992.


# Acknowledgements


This work was supported by National Science Council, Taiwan under Grant No. 86-2212-E-008-026, 87-2212-E-008-020, and 88-2212-E-008-019 and was greatly appreciated.

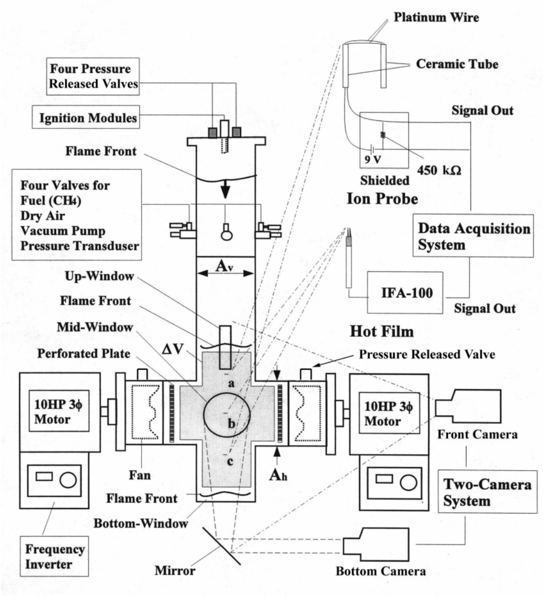



Figure 1. Schematic diagram of the two-fan apparatus with perforated plates for studies of the interaction of premixed-flame and turbulence. Also shown are three different methods for measurements of turbulent burning velocities, respectively a two-camera system, the hot-film probes, and an ion-probe method.

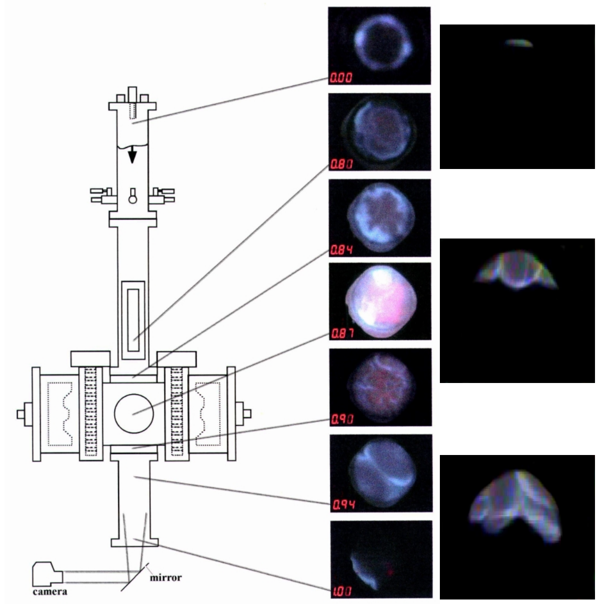



Figure 2. Typical instantaneous photographs of turbulent premixed-flame propagation at different times for $u'/S_L \approx 0.7$. Left images taken from the bottom window display the evolution of flame propagation from the ignition to the completion of burning (~1sec), whereas the three images on the right are taken from the front window.

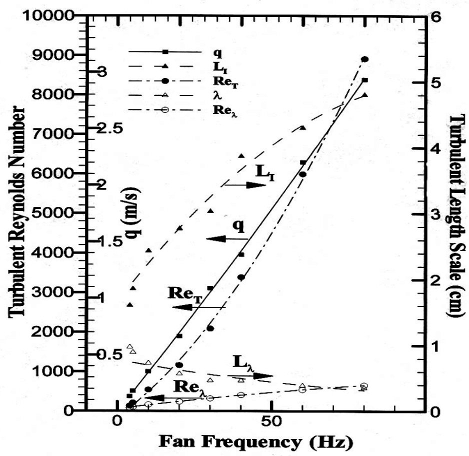



Figure 3. Variation of the overall turbulent intensity (q), the integral length scale of turbulence ($L_I$), the Taylor microscale ($L_\lambda$), the turbulent Reynolds number based on the integral scale ($Re_T$), and the Taylor Reynolds number based on the Taylor scale ($Re_\lambda$) with two-fan frequency.

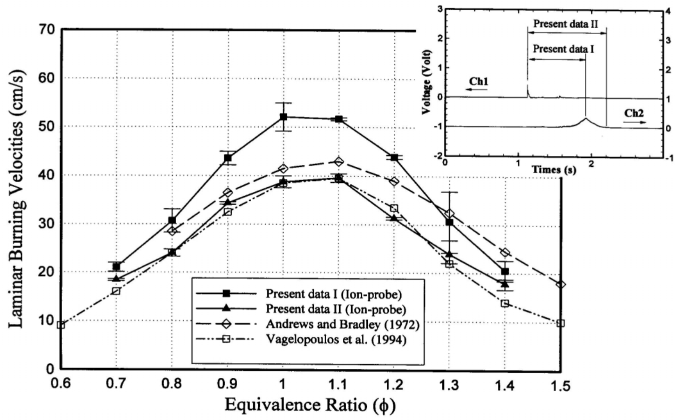
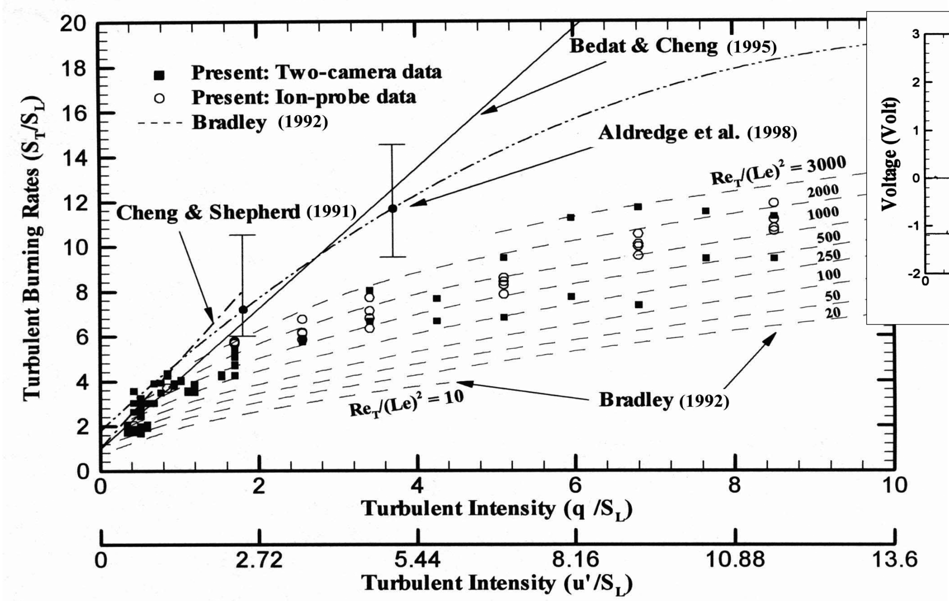



Figure 4. Values of laminar burning velocities measured in the two-fan apparatus with nonrotating fans as a function of the equivalence ratio. Also shown are measurements of Andrews and Bradley (1972) and Vagelopoulos et al. (1994) for comparison. Insert: Typical laminar signals for the ion-probe measurements, where the two probes are positioned at points "a" and "c" (see Fig. 1).



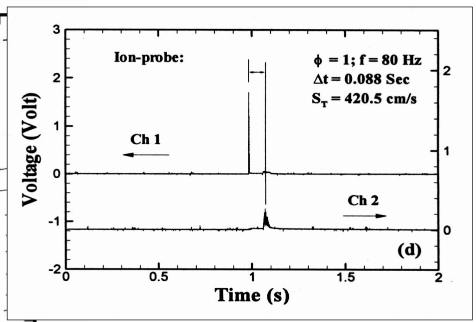




Figure 5. A comparison of turbulent burning velocities measured in the present apparatus with measurements of previous experiments using different types of burners. Insert: Typical turbulent signals for the ion-probe measurements; two probes are separated with a distance of 37cm.