A New Look at Global Quenching of Premixed Flames by Turbulence

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1 Abstracts

In 2002, Yang and Shy reported a global quenching (GQ) criterion of premixed methane-air flames by intense isotropic turbulence in a fan-stirred cruciform burner characterizing by a Bradley's Karlovitz number (K_B = 0.157 Ka) and the equivalence ratio (ϕ), where $Ka = (u'/S_L)^2(Re_T)^{-0.5}$ and u', S_L and Re_T are respectively r.m.s. turbulent fluctuating velocity, laminar burning velocity and turbulent Reynolds number. Here we *ab initio* scrutinize such criterion based on both previous and a few newly-obtained data using a modified Ka and a reaction zone Péclet number (Pe) indicating the diffusivity ratio between turbulence and chemical reaction, in which the local transport diffusivities at reactant temperature are replaced by those at mean temperature of reactants and products. This modified criterion is then compared with a newly-found ignition transition representing the boundary of different modes of turbulent kernel development showing broken reaction zones (RZ) with fileform structures. We found that critical values of Ka (Ka_c) for the onset of GQ are generally, except for very rich cases, higher than the Ka = 100 line that separates the thin and broken RZ regimes proposed by Peters. These Ka_c values verse ϕ form a parabolic curve with a maximum Ka_c = 380 occurring near ϕ = 1, indicating that GQ by turbulence not only occurs in the broken RZ regime, but has a strong dependence on ϕ. By comparing these results among ignition transition, Peters's criterion and GQ, it is found that developed turbulent flames are much harder to be globally quenched by turbulence than developing flame kernels, because the latter, previously used by Leeds group to determine GQ criteria, changes mode at lower Ka_c as compared to the former. Finally, we show that Pe is a more physically reasonable parameter than Ka to describe the aforesaid phenomena.

2 Introduction

Global quenching (GQ) of premixed flames by turbulence, a complete extinction not local quenching, is an ultimate phenomenon of turbulent premixed combustion that is a vibrant branch of science and technology with numerous applications from internal combustion engines to the explosion of supernovae. Understanding the underlying mechanism of GQ should be essential for comprehending the so-called bending effect of turbulent burning velocities (S_T) that influence virtually all important properties of premixed turbulent flames [1,2]. This can be easily appreciated from the strong bending curves found by measurements of S_T/S_L as a function of turbulent intensities (u'/S_L) in intense isotropic turbulence with negligible mean velocities [e.g., 3-5], where S_L is the laminar burning velocity. These S_T/S_L vs. u'/S_L data plots not only showed that turbulence cannot increase burning rates incessantly, but also revealed a decrease in values of S_T/S_L when values of u'/S_L are large enough [3-5] and a complete extinction (GQ) of premixed flames can eventually occur if values of u'/S_L can be further increased [6]. However, few studies are available for measurements of flame GQ by intense

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isotropic turbulence at sufficiently large turbulent Reynolds number and far from boundaries. Hence, knowledge concerning the onset of flame GQ is relatively a lack yet should never be ignored.

To the authors' best knowledge, there are currently only three, independent but relevant, experimental studies aiming to find out flame GQ criteria by turbulence [3,6,7] available to comment. The first experiment was the early work of Chomiak & Jarosiński [7], in which interaction between uniform turbulence without mean flow and developed *upward* propagating premixed flames of different fuel-air mixtures was investigated for both lean and rich flammability limit cases. Data of flame quenching by turbulence were then interpreted using the Karlovitz-Kovasznay stretch factor, $K_1 = (u'/L_I)(\delta_L/S_L)$, showing the critical values of K_1 ranging from about 10 to 20 for the occurrence of flame quenching [7], where L_I and δ_L are the integral length scale of turbulence and flame thicknesses. The second experiment was carried out in the well-known explosion bomb at Leeds University [3], where interaction between centrally-ignited, outwardly-propagating premixed flames and uniform intense turbulence was measured. These results were summarized by Bradley [3] who proposed a critical quenching criterion of $K_2Le = 6$ based on correlations of S_T/S_L to u'/S_L using K_2Le grouping for values of K_2Le ranging from 0.013 to 6, where the Lewis number $Le = \alpha/D$ indicating the ratio between thermal and mass diffusivities of the premixture and the Bradley's turbulent Karlovitz number using the Taylor length scale (λ) for isotropic turbulence was defined as $K_2 = (u'/\lambda)(\delta_L/S_L) = 0.157(u'/S_L)^2Re_T^{-0.5} = 0.157Ka$. Note that $Ka = (u'/S_L)^2Re_T^{-0.5}$ is the traditional turbulent Karlovitz number, where $Re_T = u'L_I/\nu$ and ν is the kinematic viscosity of reactants. When compared the aforesaid two studies [3,7] to which $K_2 = 0.157Re_T^{0.5}K_1 = 0.157Ka$, great discrepancy on the flame GQ criteria can be found. More specifically, the critical quenching values obtained by Chomiak & Jarosiński [7] were found to be at least one order of magnitude larger than those obtained by Bradley [3] because $0.157Re_T^{0.5} >> 1$ for large Re_T. It is also interesting to note that the quenching criteria of Chomiak & Jarosiński [7] showed a strong dependence on the equivalence ratio (ϕ) for fuels even with almost the same value of Le. Such result may reveal that Le is not sensitive enough to describe the real flame response to turbulent stretching. Furthermore, the early flame development for centrally-ignited, outwardly-propagating flames may suffer the apparent influences by various ignition conditions, such as the ignition energy and the pulse duration [8]. Moreover, smaller or developing flame kernels should be easier to be globally quenched by turbulence than do larger or developed flames. These aforementioned influences may be used to explain why critical values of the turbulent stretching factors required for flame GQ are much smaller for centrally-ignited premixed flames [3] than those for developed *upward* propagating premixed flames [7]. The third experiment to comment was a more recent work by Yang & Shy [6] who directly quantified flame GQ criteria, with and without the effect of radiative heat losses, using K_2 and ϕ, to characterize a series of experiments on interaction between sizable *downward* propagating premixed flames and intense isotropic turbulence in a fan-stirred cruciform burner. It should be noted that in Ref. [6] ignition was initiated from the top of the cruciform burner far away from the uniform turbulence region, so that the wanted flame-turbulence interactions were not influenced by the ignition. Using this experimental configuration [6], the obtained GQ criteria also showed very strong dependences on ϕ regardless of radiative heat losses, supporting the finding of Chomiak & Jarosiński [7]. Moreover, Yang & Shy [6] also found higher critical values for flame GQ than those of Bradley [3] but smaller than those of Chomiak & Jarosiński [7]. As regards the differences between the works of [7] and [6], it should be noted that the latter [6] has much wider spectra of turbulent scales with larger values of L_I, which in turn should be more effective in flame quenching.

Before further conquering experimental difficulties, what one can do at best now is to *ab initio* examine the fundamental mechanism of flame GQ based on the limited data available to solve as more as possible disputed issues encountered so far. The first important question needed concern is about the turbulent flame mode just before the occurrence of GQ (a complete extinction). Because the boundary separating quench and non-quench is very likely to be related with that separating flamelet and distributed flames or that dividing thin and broken reaction zones (RZ) [1]. The second important question to be addressed concerns the resistance of smaller flame kernels, relative to developed flames, to severe attack from fully-developed intense isotropic turbulence. To facilitate such idea, the present work compares two independent but relevant experimental findings, namely a local turbulent ignition transition based on minimum ignition energy (MIE) measurements [8] and flame GQ by turbulence [6]. Note that MIE is an ignition energy value having 50% probability of successful ignition for a given combustible mixture. The final important question we should consider is whether Ka (= $6.37K_2 = Re_T^{0.5}K_1$) is an optimal parameter for describing phenomena of flame GQ as well as for the other related issues such as identifying different turbulent combustion modes.

The objectives of this paper which are clearly separate from prior studies are: (1) to obtain new GQ data using even higher maximum counter-rotating fan frequencies, f_{max} = 182 Hz, greater than f_{max} = 170 Hz previously used in Ref. [6], (2) to compare these GQ data with other findings on different modes of combustion including ignition transition in premixed turbulent combustion and Peters's criterion for thin and broken RZ regimes, and (3) to clearly demonstrate that a large propagating flame front is much harder to be globally quenched by turbulence than a small growing flame kernel, because the latter, previously used by Leeds group to determine GQ criteria, changes mode at lower Ka_c as compared to the former. Hence, the following sections will describe briefly on how ignition transition and flame GQ are determined in the cruciform burner (see Fig. 1) and then show comparisons of these two extreme criteria between ignition transition and global quenching on the same Ka vs. ϕ plot. It should be noted that the diffusivities of ν and α used to determine K_1 or K_2 were estimated at the unburned reactant temperature (T_R) in Refs. [3,6,7]. In order to compare these quenching results with the ignition transition criterion [8], the present study uses the local diffusivities near the flame front at a mean temperature of $T_m = (T_R + T_{ad})/2$ to re-calculate values of Ka, where T_{ad} is the adiabatic flame temperature. Moreover, we introduce a RZ turbulent Péclet number ($Pe \equiv u'\eta_K/\alpha_{RZ}$) indicating the diffusivity ratio between turbulence and chemical reaction to better explain these aforesaid criteria that depend on some critical values of Pe, where η_K is the Kolmogorov length scale of turbulence and α_{RZ} is the molecular diffusivity of the reaction zone. Finally, the relations among ignition transition, flame GQ, and different modes of turbulent premixed combustion are discussed.

3 Experimental

The two studies of flame GQ by turbulence [6] and turbulent ignition transition [8] were separately carried out in the same fan-stirred cruciform burner consisting of a long vertical vessel and a large horizontal vessel capable of generating intense isotropic turbulence in the central region [4,5] (see Fig. 1). Both studies covered very wide ranges of Ka and ϕ of methane-air mixtures but with different initiation configurations. For the ignition study, initiation was taken at the center of intense isotropic region via a sharp spark electrode with controllable ignition energies and pulse durations [8]. It was found that when Ka is greater than some critical values ($Ka_{c1} \approx 8 \sim 26$) depending on ϕ, the shape of flame kernel can change drastically from a laminar torus to broken pieces with filiform structures (see left images of Fig. 1) and corresponding values of MIE required for such transition show a drastic change from a modest increase to an abrupt increase, revealing ignition transition [8]. For the quenching study, a sizable downward-propagating flame was initiated from the top of the vertical vessel to interact with central intense isotropic turbulence without any influence from ignition [6]. In it fully-developed turbulent flames can change their pattern drastically from downwardly-propagating with turbulent-flamelet structures to randomly-propagating with distributed-like structures (see right images of Fig. 1) just before the occurrence of flame GQ which also depends on some critical values of Ka (Ka_{c2}) and ϕ [6].

Figure 2a shows variations of Ka_{c2} with ϕ for both pure CH_4/air flames and CH_4/CO_2/air flames plotted with the two accessible domains determined by the maximum values of Ka (Ka_{max}) using f_{max} = 182 Hz ($u' \approx$ 8.5 m/s), where the empty symbols are previous Ka_{c2} data re-calculated using local diffusivities near the flame front at T_m and the solid and "X" symbols are the newly-obtained data. Note that these "X" symbols are the present ϕ-limits indicating that pure CH_4 and/or CO_2-diluted flames, respectively at $0.64 < \phi < 1.35$ and/or at $0.87 < \phi < 1.03$, cannot be globally quenched even when the maximum values of Ka achievable in the present experimental configuration are applied. Thus, the flame GQ regimes marked by the grid-line areas (Fig. 2a) can be identified. When compared pure CH_4 flames with 60% CO_2-diluted flames, the leanest and richest values of ϕ that can be conducted in the cruciform burner are reduced from 0.6 to 0.73 for the lean side and from 1.45 to 1.23 for the rich side. Figure 2a also shows that values of Ka_{c2} increase drastically as values of ϕ gradually approach towards $\phi = 1$ from either lean or rich sides for both pure and diluted flames. In it the flame GQ boundary for CO_2-diluted flames including both real measured data (the solid line) and the anticipated curve (the dash line) may be used to form a complete Ka_{c2}-ϕ curve assuming that the maximum Ka_{c2} occurs near $\phi = 1$. Following the same trend of CO_2-diluted flames, we predict the anticipated Ka_{c2}-ϕ curve for pure CH_4/air flames, and these results are plotted on Fig. 2b for comparison.

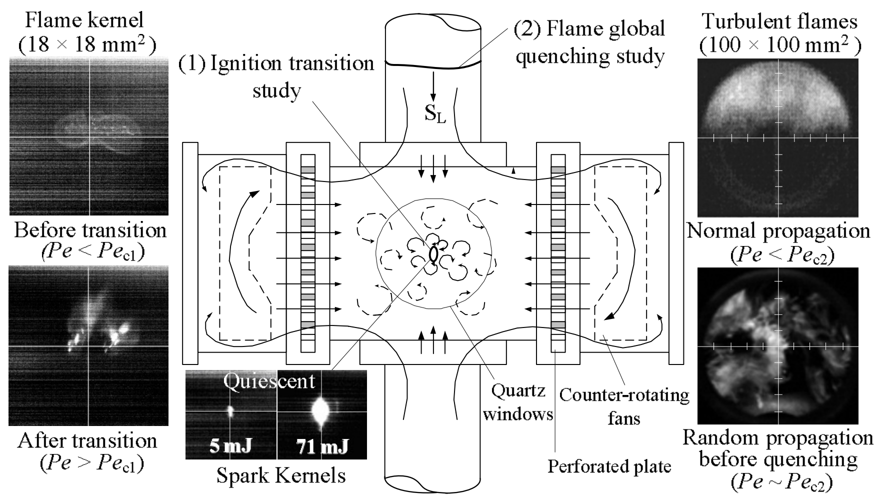

Figure 1. Schematic of the cruciform burner with centrally-ignited kernels for ignition transition study and with downward-propagating flames for global quenching study. Left two images are taken after ignition, showing typical flame kernels before and after the ignition transition, where the same rich CH_4-air mixtures at $\phi = 1.2$ are applied and the critical $Ka_{c1} \approx 8$. Right two images display typical CH_4-air premixed flames at modest $Ka \approx 1 << Ka_{c2}$ for flamelet propagation and at very large $Ka \approx 100$ for distributed-like flames just before global quenching where the same lean CH_4-air mixtures at $\phi = 0.6$ are applied and the critical $Ka_{c2} \approx 104$. Also shown below is the dependence of initial kernel sizes on ignition energy.

4 Results and Discussion

Figure 3a presents comparisons of the two extreme criteria of both ignition transition (Ka_{c1}) and flame GQ (Ka_{c2}) as a function of ϕ using the same methane-air mixtures, in which the same definition of Ka is applied and the subscripts c1 and c2 represent critical values of Ka respectively for ignition transition and flame GQ. Also plotted is the scaling criterion (the Ka = 100 line) proposed by Peters [1] for the boundary between thin and broken RZ regimes without considering the influence of ϕ. For ignition transition, values of $Ka_{c1} \approx 8 \sim 26$ depending on ϕ with the perplexing *minimum* Ka_{c1} occurring near $\phi = 1$, while for flame GQ much higher critical values of Ka are found where $Ka_{c2} \approx 29$ to 380 depending also on ϕ but with the *maximum* Ka_{c2} occurring near $\phi = 1$. Nevertheless, values of Ka_{c1} for the transition are found to be one order smaller than that anticipated by Peters (Ka_{c2} = 100) [1] for developed turbulent flames. This result shows that developing flame kernels have weaker reaction strength than developed turbulent flames, because the former does not have a large pool of radicals behind the flame. Thus, centrally-ignited, developing flame kernels tend to change mode at lower critical values of Ka as compared to developed turbulent flames. Such result further reveals a fact that the criteria for flame GQ cannot be correctly defined from centrally-ignited combustion experiments in the fan-stirred cruciform burner because the condition of flame GQ by turbulence can be underestimated or compensated by providing sufficiently high ignition energies. This is why the ignition is initiated from the top of the long vertical vessel for the study of flame GQ. Using such ignition arrangement, a sizable downwardly-propagating premixed flame (at least 10 cm in diameter, not just a small flame kernel) can be generated to interact with intense isotropic turbulence without any influence from ignition. Our flame GQ result in Fig. 3a reveals three key points. First, even when $Ka_{c2} > 100$ beyond the broken RZ regime, the turbulent CH_4 flames at $0.6 \leq \phi \leq 1.3$ can still be alive even having very slow burning rates (see the bottom right image on Fig. 1 having islands or pockets). Secondly, in order to quench globally fully-developed lean premixed CH_4 flame, the required Ka_{c2} must be increased drastically from at least 104 at $\phi = 0.6$ to as much as 380 (predicted value) when $\phi = 1.0$. Thirdly, to the other end of Fig. 3a, very rich CH_4 flames are easier to be globally quenched by turbulence than very lean CH_4 flames, by which $Ka_{c2} \approx 29$ at $\phi = 1.45$, a value that is much smaller than the Peters's predication [1] as well as the Bradley's criterion [3], showing the strong influence of ϕ.

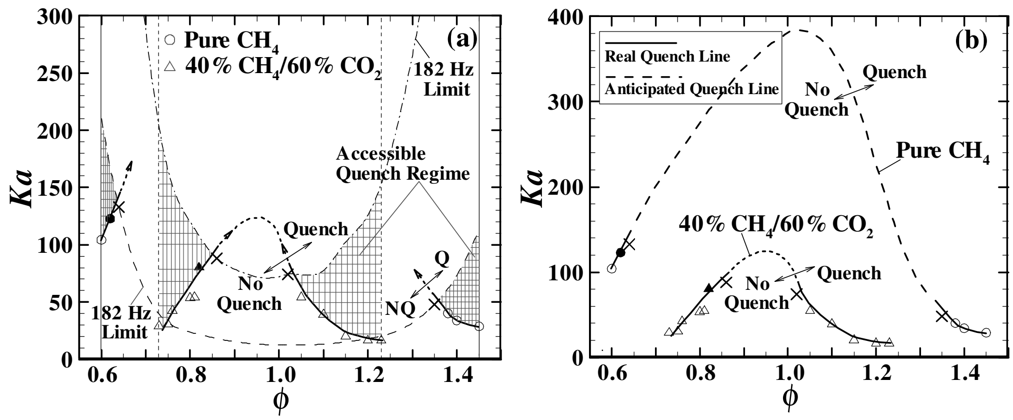

Figure 2. (a) Accessible domains and measured critical values of turbulent Karlovitz number for global quenching at achievable equivalence ratios for CH_4/air and CH_4/CO_2/air flames. (b) Values of Ka_{c2} plotted against ϕ, where the solid lines are real quenching lines obtained from the actual data points from (a) and the dashed lines are the anticipated quenching lines.

Now we re-plot the same data from Fig. 3a in terms of Pe as a function of ϕ, and the results are presented in Fig. 3b. As seen, these three datum groups with very different tendencies in the semi-log Ka-ϕ plot (Fig. 3a) can be transformed into a single coherent style in the Pe-ϕ plot where values of Pe only vary from about 4 to 7.5. An important question arises. Why is the parameter Ka not a most appropriate parameter to describe the influence of turbulence on the flame kernel development? The reason is that the physical mechanism to determine whether a flame kernel will successfully form should be the energy balance between the heat input and the heat loss [8]. Thus, the mechanism of flame kernel formation depends on the diffusivity ratio between turbulence and chemical reaction (Pe) rather than their corresponding response time ratio (Ka). It should be noted that the effective $Ka = 100$ line (Peters's prediction) re-plotted in Fig. 3b in terms of Pe and ϕ uses the same values of S_L and transport and turbulence properties as those used in ignition and quenching experiments. We found that for $0.6 < \phi < 1.3$, values of Pe_{c2} for flame GQ are greater than that of the Peters's predication having the same trend with the maximum Pe_{c2} occurring near $\phi = 1$. However, when $1.3 < \phi < 1.45$, global quenching of very rich CH_4 turbulent flames occurs earlier, where values of Pe_{c2} are smaller than that of the Peters's predication. This is because for very rich CH_4 flames, the abundant unburned fuel in the product side near the flame front can lead to higher degree of oxygen deficiency in the flame RZ. From chemical considerations, when the fuel is consumed in the inner layer, the radicals are depleted by chain-breaking reactions and the rate-determining reaction in the inner layer is very sensitive to the presence of H radicals [9]. Furthermore, the depletion of H radicals is much more rapidly in rich CH_4 flames than in lean CH_4 flames [10] that may be used to explain why rich CH_4 flames are easier to be globally quenched by turbulence than lean CH_4 flames.

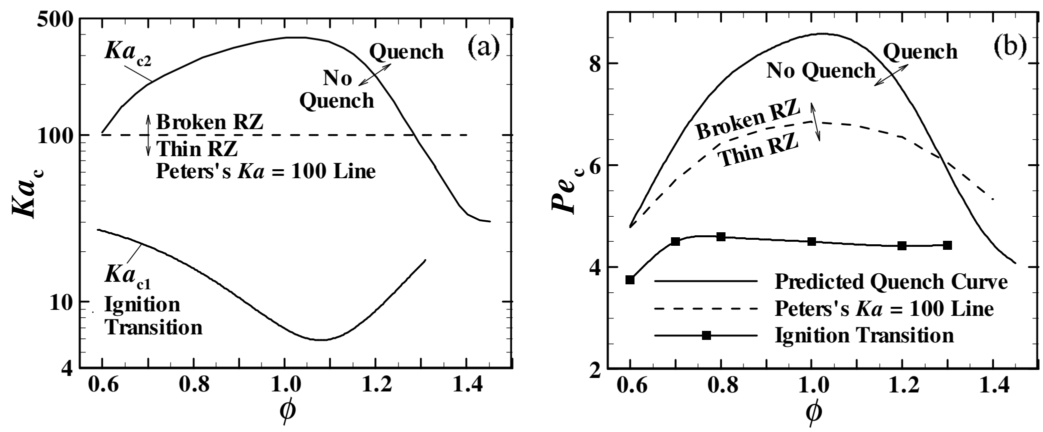

Figure 3. (a) The critical turbulent Karlovitz number as a function of the equivalence ratio for both ignition transition and flame global quenching along with the Ka = 100 line proposed by Peters [1]. (b) Same as (a), but plotted for the critical reaction zone turbulent Péclet number against ϕ.

5. Conclusion

By comparing different criteria of flame GQ and ignition transition with the Peters criterion for thin and broken reaction zones, the present study (Fig. 3) shows that flame GQ occurs beyond the Peters prediction. However, for kernel development, the ignition transition occurs earlier than the Peters criterion because the latter is for flame development of which there is a large radical pool behind the flame. It is found that the RZ Péclet number can provide a better physical description for the aforesaid phenomena especially for the ignition transition than does the turbulent Karlovitz number. This indicates that the mechanisms of ignition transition (regular torus kernels versus broken kernels) and flame global quenching depend on the diffusivity ratio between turbulence and chemical reaction (Pe) rather thantheir corresponding response time ratio (Ka).

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