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Spark ignition probability and minimum ignition energy transition of the lean iso-octane/air mixture in premixed turbulent combustion

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ABSTRACT

This paper measures turbulent spark ignition probability and minimum ignition energy (MIE) of the pre-vaporized iso-octane/air mixture at an equivalence ratio $\phi = 0.8$ at 373 K with $Le \approx 2.98$ over a wide range of turbulent intensities (u'/S_L), where Le is the mixture's effective Lewis number and S_L is the laminar burning velocity. Ignition experiments using a fixed 2-mm electrode gap are conducted in a large dual-chamber, constant-temperature/pressure, fan-stirred 3D cruciform burner capable of generating near-isotropic turbulence. Spark discharges having nearly square voltage and current waveforms are created for accurate determination of the ignition energy (E_{ig}) across the electrodes. MIE $\equiv E_{ig(50\%)}$ that is determined statistically from many repeated experiments at a given condition using a range of E_{ig} to identify an overlapping energy band within which ignition and non-ignition coexist even at the "same discharge E_{ig}", where the subscript "ig(50%)" indicates 50% ignitability. Results show that the increasing slopes of $\mathrm{MIE_T}/\mathrm{MIE_L} = \Gamma$ versus u'/S_L change drastically from linearly to exponentially when u'/S_L is greater than a critical value of 4.8, which is much smaller than previous rich methane data ($Le > 1$) at $\phi = 1.2$ with $(u'/S_L)_c \approx 16$ and at $\phi = 1.3$ with $(u'/S_L)_c \approx 24$, revealing MIE transition. The subscripts T and L represent turbulent and laminar properties. When a reaction zone Péclet number $Pe_{RZ} = u'\eta_k/\alpha_{RZ}$ is used for scaling, it is found that both present lean iso-octane and previous methane data can be collapsed onto a general correlation of $\Gamma_1 = 1 + 0.4Pe_{RZ}$ in the pre-transition and $\Gamma_2 \sim {Pe_{RZ}}^4$ in the post-transition with the transition occurring at $(Pe_{RZ})_c \approx 4.2$, showing similarity on MIE transition. η_k is the Kolmogorov length scale of turbulence and α_{RZ} is the reaction zone thermal diffusivity estimated at the instant of kernel formation.

1. Introduction

In the past roughly 80% papers published in Combustion and Flame applied methane as a fuel, but papers for liquid fuels such as gasoline and its surrogates were much less in number [1]. Indeed, our combustion community needs to study combustion characteristics of gasoline and its surrogates in more depth. Since iso-octane is the major surrogate component for gasoline [2,3], understanding of turbulent flame initiation of lean iso-octane through the two-way interaction between spark kernel and turbulence, as the first level of simplification, is important to spark ignition (SI) engine operation at fuel-lean conditions for better fuel economy and emissions [4]. Even for just a small improvement of fuel efficiency in SI engines, it will have a significant impact on economy and environment [4]. Hence, the first objective of this work is to measure spark ignition characteristics and minimum ignition energy (MIE) of the lean iso-octane/air mixture at an equivalence ratio $\phi = 0.8$ and $T = 373$ K as a function of turbulent intensities (u'/S_L) in a large dual-chamber, constant-temperature/pressure, fan-stirred explosion facility capable of generating near-isotropic turbulence, where S_L is the laminar burning velocity. To the best knowledge of the authors, iso-octane MIE data measured directly from the spark electrodes are very rare in literature.

Ignition plays an important role in the performance of internal combustion engines [4]. Probably, the simplest way to ignite a combustible mixture in a laboratory experiment is to use a spark generated by a pair of electrodes with a certain amount of ignition energy (E_{ig}), commonly known as the minimum ignition energy [5]. Information of MIE for ignition hazards of fuels is crucial for the risk assessment of accidental explosion in industrial and aviation safety [6]. Also, MIE is an important property to most combustion devices [6,7]. There are many valuable data in literatures not only for MIE itself but also for the effects of many parameters on MIE, most in quiescent condition and some with flow considerations, via experimental, numerical, and modeling approaches (e.g., [5–31] among many others). These parameters of interest include:

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(1) the electrode breakdown characteristics (e.g., type of discharge, discharged voltage/current and pulse duration time), (2) the electrode characteristics (e.g., material, geometry, size and gap), (3) the flow characteristics (e.g., type of flow, turbulent velocity/length scales, pressure and temperature), and (4) the mixture characteristics (e.g., equivalence ratio, type of fuel). A spark ignition experiment that can be accurately reproduced by other groups should provide these aforesaid parameters as well as the discharged E_{ig}. To obtain an accurate E_{ig}, it is necessary to generate well-controlled current $I(t)$ and voltage $V(t)$ waveforms (best in square forms with little fluctuations) across the positive and negative electrodes during the pulse duration time Δt_p. Thus, the discharged E_{ig} (not the stored energy of inductive spark source) can be accurately measured across the electrode gap by directly integrating the product of discharged $I(t)$ and $V(t)$ within Δt_p. Unfortunately, this is frequently not the case in the available literatures. The more we study the spark ignition problem, the more we realize the difficulties in obtaining an accurate E_{ig}. These difficulties may cause some confusion on the determination of MIE, as discussed below.

First, it should be noted that the electrical breakdown at the electrode gap from an inductive spark ignition source is statistical in nature with inherent perturbations in the breakdown energy, the subsequent discharge, and the location of the spark channel (see [7–14] and references therein). To be shown later, these perturbations can result in either ignition or non-ignition even at the “same discharged E_{ig}” for a given condition under which all the above-mentioned parameters for the breakdown, electrode, flow, and mixture characteristics are kept the same [7]. It should be noted that the successful ignition event has to fulfill the three evolution steps from the formation of discharged spark to the formation of flame kernel and its subsequent flame propagation without global quenching, otherwise belonging to unsuccessful ignition (non-ignition). Based on inherent perturbations, spark ignition should be approached as a statistical rather than a threshold phenomenon. This is because MIE is a probabilistic variable, not a threshold value. Many repeated ignition experiments for a given condition with a range of E_{ig} are therefore required to identify an overlapping energy band within which ignition (Go) and non-ignition (No Go) coexist as always observed in engineering test data [e.g., 7–14,17,19,20,22,23,26-28,31]. MIE is then determined at the 50% ignitability (MIE $\equiv E_{ig(50\%)}$ [e.g., 6–14]). For clarity, we will demonstrate in due course exactly what the statistical nature of spark ignition is and how to determine the spark ignition probability over a wide range of u'/S_L by using the logistic regression method.

Second, a MIE transition deserves comments. Huang et al. [17] were the first to report MIE transition based on ignition experiments of randomly-stirred gaseous methane/air mixtures at the equivalence ratio $\phi = 0.6$ using a spark-electrode with a fixed electrode gap of $d_{gap} = 2$ mm in a large *non-heated* fan-stirred cruciform burner capable of generating a sizable near-isotropic turbulence region. In [17], $\mathrm{MIE_T/MIE_L} \sim (u'/S_L)^{0.7}$ in the range of $0 < u'/S_L < 23$, while $\mathrm{MIE_T/MIE_L} \sim (u'/S_L)^7$ when $u'/S_L > 23$, showing MIE transition, where the subscripts T and L represent turbulent and laminar properties. In 2010, Shy et al. [22] reported complete MIE data sets of gaseous methane/air mixtures at six different equivalence ratios ($\phi = 0.6$, 07, 0.8, 1.0, 1.2, 1.3), each covering a wide range of u'/S_L at $d_{gap} = 2$ mm. In [22], it was found that the increasing slopes of $\mathrm{MIE_T/MIE_L}$ with u'/S_L change drastically from linearly to exponentially when values of u'/S_L are greater than some critical values depending on ϕ. Furthermore, these scattering $\mathrm{MIE_T/MIE_L}$ data depending on u'/S_L and ϕ can be collapsed onto a single curve when scales with a reaction zone Péclet number, $Pe_{RZ} = u'\eta_k/\alpha_{RZ}$, showing the first and fourth power dependence before and after MIE transition at a critical $Pe_{RZ} \approx 4.2$–4.5 except for the case of $\phi = 0.6$ where $Pe_{RZ,c} \approx 3.6$ [22]. η_k is the Kolmogorov length scale of turbulence and $\alpha_{RZ} \sim S_L\delta_L$ is the thermal diffusivity estimated at the instant of kernel formation, where δ_L is the laminar flame thickness. The results in [22] revealed a self-similar spark ignition phenomenon characterizing by Pe_{RZ}, a surface diffusivity ratio between turbulence and chemical reaction just around the spark ignition kernel. Moreover, Renou and co-workers [28] independently verified the aforesaid MIE transition using laser-induced spark ignition of lean turbulent methane/air mixtures in decaying homogenous wind-tunnel turbulence. Note that these two previous studies applying different ignition systems (conventional electrode [22] versus laser [28]) in different flow configurations (fan-stirred near-isotropic turbulence [22] versus decaying homogenous wind-tunnel turbulence [28]) found the same MIE transition phenomenon, suggesting that MIE transition may be a universal phenomenon. An interesting question may arise. Could the aforesaid MIE transition found in gaseous methane fuel be applicable to SI engines using liquid fuel such as iso-octane? To the first level of approximation, we address such question by measuring MIE of the lean iso-octane/air mixture at $\phi = 0.8$ and $T = 373$ K with a wide range of u'/S_L, where the effective Lewis number of the mixture (Le) is about 2.98 as reported in [32].

Third, an unexpected turbulent ignition phenomenon at room temperature [33] also deserves comments. In [33], the authors discovered that turbulence can facilitate ignition through differential diffusion for $Le > 1$ flames (the hydrogen/air mixture at $\phi = 5.1$ with $Le \approx 2.3$ and the n-butane/air mixture at $\phi = 0.7$ with $Le \approx 2.1$), when applying a pair of cantilever electrodes of 0.25-mm diameter with small electrode gaps ($d_{gap} \leq 0.8$ mm) in near-isotropic turbulence generated by a fan-stirred burner. They found that a fixed spark discharge voltage at $d_{gap} = 0.58$ mm which is unable to ignite the hydrogen/air mixture at $\phi = 5.1$ (Le is sufficiently greater than unity) in both quiescence and weak turbulence can nevertheless ignite the same mixture in intense turbulence up to $u' = 5.4$ m/s. This suggested that $\mathrm{E_{ig}}$ required for successful ignition in intense turbulence can be smaller than that in quiescence, which differs with the classic conclusion of the turbulent effect on E_{ig} and/or MIE [e.g., 5,7,9,11,15,17-20,22,26,28,29]. However, we expect that larger d_{gap} plays a different role in turbulent facilitated ignition (TFI) for $Le > 1$ flames. This is because Shy and co-workers [22] reported that turbulence renders ignition more difficult and thus leads to the aforesaid MIE transition regardless of Le for methane/air mixtures ($\phi = 0.6$–1.3; $0.97 \leq Le \leq 1.04$), by using a larger $d_{gap} = 2$ mm in near-isotropic turbulence generated in a large fan-stirred cruciform bomb. Recalling that Lewis & von Elbe had long showed: all $\mathrm{MIE_L}$ data curves as a function of d_{gap} for any given mixtures (e.g., Figs. 163,165 in [5]) had a rapid upturn at a critical d_{gap} called the quenching distance (d_q), where $\mathrm{MIE_L}$ increased drastically when $d_{gap} < d_q$ (the smaller d_{gap}, the more drastic increase of $\mathrm{MIE_L}$). When $d_{gap} > d_q$, $\mathrm{MIE_L}$ had nearly the same values over a considerable range of d_{gap} (Figs. 163,165 of [5]). Such quenching distance effect was also found by numerical simulations using detailed chemical kinetics [21]. Further, a report on survey of hydrogen combustion properties, using Table 9 in [5] to plot d_q versus ϕ, showed that $d_q \approx 4$ mm for the H_2/air mixture at $\phi = 5.1$ (Fig. 12 in [34]). Since Wu et al. [33] applied small electrode gaps ($d_{gap} = 0.3$, 0.58, 0.8 mm$<<d_q$), it is also interesting to know whether TFI for $Le>1$ exists for a larger $d_{gap} = 2$ mm when using iso-octane as a fuel with sufficiently large Le ($\approx 2.98 > 1$).

This work applies the same ignition system as in [7] and the same 2-mm thick electrodes with sharp ends at $d_{gap} = 2$ mm as in our previous methane studies [7,17,19,22,26]. A series of well-controlled lean iso-octane ignition experiments are conducted in a double-chamber, constant-temperature, constant-pressure, fan-stirred cruciform burner to measure values of MIE as a function of u'/S_L, as to be described in the next section. By comparing the