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Brief Communications

Is turbulent facilitated ignition through differential diffusion independent of spark gap?

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ABSTRACT

In 2014, Wu et al. discovered an unexpected result. Turbulence can facilitate ignition through differential diffusion when the effective Lewis number (*Le*) of mixtures is sufficiently larger than unity using small electrode gaps ($d_{gap} \le 0.8$ mm) in near-isotropic turbulence generated by a fan-stirred burner. This suggested that the required minimum ignition energy (MIE) in intense turbulence can be smaller than that in quiescence (Wu et al. did not measure MIE). This work explores whether the aforesaid turbulent facilitated ignition (TFI) for $Le > 1$ is independent of d_{gap}. We apply the same hydrogen mixtures at the equivalence ratio $\phi = 5.1$ ($Le \approx 2.3$) and $\phi = 0.18$ ($Le \approx 0.3$) as Wu et al. in our large fan-stirred cruciform bomb capable of generating near-isotropic turbulence to measure values of MIE as a function of d_{gap} at both quiescence and intense turbulence (the rms turbulent fluctuating velocity $u' = 5.4$ m/s) conditions. A drastic fall of values of laminar and turbulent MIE (MIE_L and MIE_T) with increasing d_{gap} is observed. TFI only occurs for $Le > 1$ ($\phi = 5.1$) and it is restricted at smaller $d_{gap} = 0.58$ mm, where $MIE_L = 61.5$ mJ >> $MIE_T = 26$ mJ (0.25-mm tungsten electrodes) and $MIE_L = 255.5$ mJ >> $MIE_T = 36.8$ mJ (2-mm tungsten electrodes) in support of Wu et al.'s finding. However, we discover that the MIE_L and MIE_T curves versus d_{gap} can cross each other at larger d_{gap}, at which no TFI for $Le > 1$ at $d_{gap} = 2$ mm where $MIE_L = 0.52$ mJ << $MIE_T = 17.3$ mJ (2-mm tungsten electrodes). This interesting result depending on d_{gap} should be disseminated in our combustion community for stimulating further research.

Law and co-workers [1] discovered that turbulence can facilitate ignition through differential diffusion when the effective Lewis number (*Le*) of mixtures is sufficiently greater than unity. They applied a pair of cantilever electrodes of 0.25-mm in diameter with small electrode gaps ($d_{gap} \le 0.8$ 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 assured of being unable to ignite the hydrogen/air mixture at the equivalence ratio $\phi = 5.1$ ($Le \approx 2.3 > 1$) in both quiescence and weak turbulence can nevertheless ignite the same mixture in intense turbulence up to the rms turbulent fluctuating velocity $u' = 5.4$ m/s. This suggested that the ignition energy (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} (e.g., [2–10]). For the hydrogen/air mixture at $\phi = 0.18$ with $Le \approx 0.3 < 1$, no turbulent facilitated ignition (TFI) was found with $d_{gap} \le 0.8$ mm [1]. A question may then arise. Is the aforesaid TFI for $Le > 1$ independent of d_{gap}? Larger d_{gap} is expected to play a different role in turbulent ignition. This is because Shy and co-workers [6–8,10] reported that turbulence renders ignition more difficult and thus leads to an ignition transition regardless of *Le*, by using 2-mm electrodes with a larger $d_{gap} = 2$ mm in near-isotropic turbulence generated in a large fan-stirred cruciform bomb (see Fig. 1 of [11]). Across the transition, the increase of $E_{ig,T}$ with increasing u' varies from linearly to exponentially, where the subscript T represents the turbulent property. Using the same rich and lean H_2/air mixtures and electrodes as in [1] in our cruciform bomb together with the well-established ignition system [10] allows measuring E_{ig} here of high accuracy and/or minimum ignition energy (MIE) as a function of d_{gap} at both quiescence ($u' = 0$) and intense turbulence ($u' = 5.4$ m/s) conditions, which reveals the subtle detail of spark ignition phenomena.

It is known that laminar MIE (MIE_L) data increase drastically when $d_{gap} < d_q$, where d_q is a critical d_{gap} called the quenching distance that may be related to the critical radius of the developing flame kernel for successful flame initiation in the classic thermal-diffusion theory [2,12]. When $d_{gap} > d_q$, MIE_L is roughly the same over a considerable range of d_{gap} (Figs. 163,165 of [2]).

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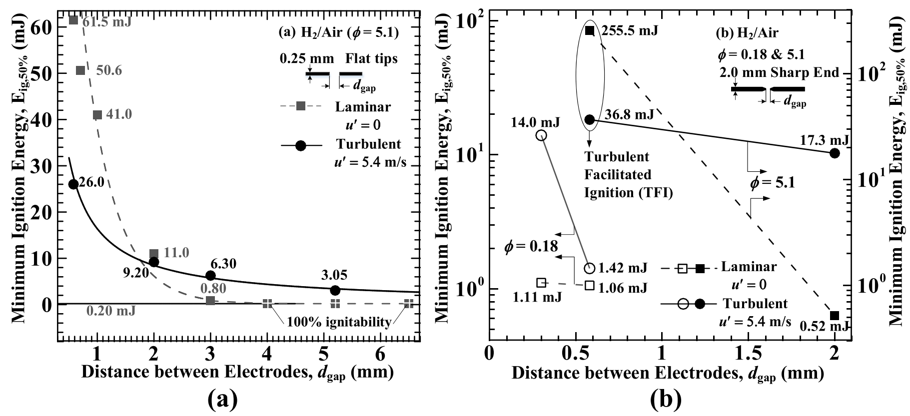

Fig. 1. (a) MIE comparison between laminar and intense turbulence cases over a wide range of d_{gap} for the H_2/air mixture at $\phi = 5.1$ with $Le \approx 2.3$ using the 0.25-mm electrodes same as [1]. (b) Effect of ϕ and u' on MIE at three selected d_{gap} for both lean and rich H_2/air mixtures at $\phi = 0.18$ and 5.1 with $Le \approx 0.3 \ll 1$ and $Le \approx 2.3 \gg 1$.

Note that for the H_2/air mixture used in [1] at $\phi = 0.18$ ($Le \approx 0.3$) and 5.1 ($Le \approx 2.3$), $d_q \approx 2.8$ mm and 4 mm, respectively (Table 9 in [2] and Fig. 12 in [13]). Since Wu et al. [1] applied a small $d_{gap} = 0.58$ mm at $Le \approx 2.3$, it may be reasonable to postulate that MIE_L could be possibly higher than turbulent MIE (MIE_T) when $d_{gap} << d_q$. However, the factor of $d_{gap} << d_q$ alone fails to explain the Le dependence of TFI [1]. To account for the Le effect we further consider the critical flame radius (R_c), below which flame propagation may not be possible [14,15]. As noted by Ju and coworkers, R_c increases with Le [15]. For very rich and very lean H_2/air mixtures, it appears that $R_c > d_q$ when $Le >> 1$ and conversely $R_c < d_q$ when $Le << 1$ [15]. As such, TFI could occur at $Le >> 1$ when $d_{gap} << d_q$, but it is not likely to occur at $Le << 1$ even with $d_{gap} << d_q$. Here it is interesting to know if TFI remains existent at $Le \approx 2.3$ for larger $d_{gap} > 0.58$ mm.

Before presenting E_{ig} and/or MIE versus d_{gap} results, two points deserve to comment. First, there are many valuable data in literature not only for MIE itself but also for the effects of many parameters on MIE (e.g., [3–10,16,17] among others). These parameters include: (i) electrical breakdown characteristics i.e. type of discharge, discharged voltage/current, pulse duration time; (ii) electrode characteristics i.e. material, geometry, size, gap; (iii) flow characteristics i.e. type of flow, turbulent velocity/length scales, pressure, temperature; (iv) mixture characteristics i.e. equivalence ratio, phase of fuel. For accurate reproduction of a spark ignition experiment, these aforesaid parameters as well as the discharged E_{ig} are needed. Each value of the discharged E_{ig} should be directly measured across the gap between electrodes by integrating the product of discharged current and voltage waveforms (best in square waveforms with little fluctuations) within the pulse duration time (Δt_p) [6–8,10]. Second, MIE is a statistical quantity in nature owing to inherent perturbations in the electrical breakdown characteristics (e.g., [2,4,10,17]). These perturbations can result in either ignition or non-ignition even at the "same discharged E_{ig}" for a given condition. Therefore, MIE measurements should be approached as a statistical rather than a threshold phenomenon (MIE is a probabilistic variable, not a threshold value). Repeated ignition experiments for a given condition with a range of E_{ig} are thus required to identify MIE at 50% ignitability (e.g., [7,16,17] among others). We present an example of spark ignition probability versus different energy level at $d_{gap} = 2$ mm in quiescence in the Supplemental Material [18], where both "Go" (ignition) and "No Go" (non-ignition) coexist within an overlapping energy band. $MIE \equiv E_{ig(50\%)}$ is determined by the logistic regression method [19]. In this work we apply the same spark ignition circuit with one-shot mode as in our previous studies [8,10], of which the range of E_{ig} lies between the smallest $E_{ig} = 0.2$ mJ (breakdown voltage = 15 kV, $R_\Omega = 2$ MΩ, $\Delta t_p = 10$ µs) and the largest $E_{ig} = 300$ mJ (15 kV, $R_\Omega = 5$ kΩ, $\Delta t_p = 500$ µs) where R_Ω is the loading resistance.

Figure 1(a) presents the effect of d_{gap} on both MIE_L and MIE_T at $u' = 5.4$ m/s of the same hydrogen/air mixture at $\phi = 5.1$ with $Le \approx 2.3$ using the same thin 0.25-mm tungsten electrodes as in [1]. A drastic fall of MIE_L with increasing d_{gap} is observed when $d_{gap} < d_q \approx 4$ mm, where MIE_L at $d_{gap} = 0.58$ mm (61.5 mJ) is 77 folds larger than $MIE_L = 0.8$ mJ at $d_{gap} = 3$ mm. Further, when $d_{gap} = 4$ mm, 5.2 mm and 6.5 mm, we find that such rich hydrogen mixture is extremely easy to ignite having 100% ignitability to our lowest $E_{ig} = 0.2$ mJ (see the marked square symbols in Fig. 1a), suggesting MIE_L is much less than 0.2 mJ within 4 mm $\le d_{gap} \le$ 6.5 mm. The monotonic decrease in MIE_L at $Le \approx 2.3$ with increasing d_{gap} in Fig. 1(a) is consistent with the effect of R_c [14,15] or d_q [2,12]. As to the intense turbulence case ($u' = 5.4$ m/s), when $d_{gap} = 0.58$ mm, $MIE_T = 26.0$ mJ $<< MIE_L = 61.5$ mJ. This quantitative MIE result supports the previous qualitative result of [1] that for $Le > 1$ mixtures, turbulence can facilitate ignition. But we find that such TFI phenomenon only occurs at small d_{gap}. Interestingly, the MIE_L and MIE_T curves in Fig. 1(a) cross each other when $d_{gap} \ge 2$ mm. Specifically, at $d_{gap} = 3$ mm, $MIE_T = 6.3$ mJ $>> MIE_L = 0.8$ mJ. Similarly, when $d_{gap} = 5.2$ mm, $MIE_T = 3.05$ mJ $>> MIE_L$ that is much less than 0.2 mJ. In brief summary, at $Le \approx 2.3$, the effect of $d_{gap} << d_q \approx R_c$ (4–5 mm estimated from Fig. 1(b) in [1]) severely increases MIE_L, owing possibly to the huge heat loss to spark electrodes. It might then be easier to, as argued in [1], survive for a flame kernel that moves with the turbulent wind away from the spark gap, leading to TFI. However, TFI seems to weaken and then to disappear with the continual enlargement of d_{gap}, as shown in Fig. 1(a).

To compare the former result ($Le > 1$) with a very lean case ($Le < 1$) as well as to test the thickness effect of spark electrodes, we briefly present the results with a pair of thick tungsten electrodes (2-mm in diameter), which are shown in Fig. 1(b). At $\phi = 0.18$, when $d_{gap} = 0.3$ mm, $MIE_L = 1.11$ mJ at $u' = 0 << MIE_T = 14$ mJ at $u' = 5.4$ m/s, while $MIE_L = 1.06$ mJ at $u' = 0 < MIE_T = 1.42$ mJ at $u' = 5.4$ m/s when $d_{gap} = 0.58$ mm. Although there is no TFI for $Le < 1$ mixture, here, MIE_T seems to approach MIE_L toward larger d_{gap}. Note that when $Le << 1$, due to $R_c << d_q$, $MIE_L \sim R_c{}^3$ is less sensitive to the effect of $d_{gap} << d_q$ [15]. Therefore, it is not surprising that at $Le = 0.3$, TFI does not occur in Fig. 1(b) even when $d_{gap} << d_q$, consistent with the finding in [1]. As shown in Fig. 1(b) for $Le > 1$ mixture, TFI is still restricted at smaller $d_{gap} = 0.58$ mm, where $MIE_L = 255.5$ mJ $>> MIE_T = 36.8$ mJ at $u' = 5.4$ m/s having the same trend as Fig. 1(a). We find no TFI at

$d_{gap} = 2$ mm (Fig. 1b), because MIE_L is only 0.52 mJ which is much less than $MIE_T = 17.3$ mJ at $u' = 5.4$ m/s. The possible reason for ignition facilitated in intense turbulence for $Le > 1$ flame may, as argued in [1], be that the flame segments intensified by the negative stretch move away from incipient extinction and serve as local ignition sources. Since the state of incipient extinction may be a direct result of $d_{gap} << R_c$, the present finding that TFI may not hold for arbitrary d_{gap} thus confirms this point. In short, TFI depends on d_{gap}, which deserves to be disseminated in our combustion community.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.combustflame.2017.06.022.

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